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# Glacier and Climate Studies West Gulkana Glacier and Environs, Alaska

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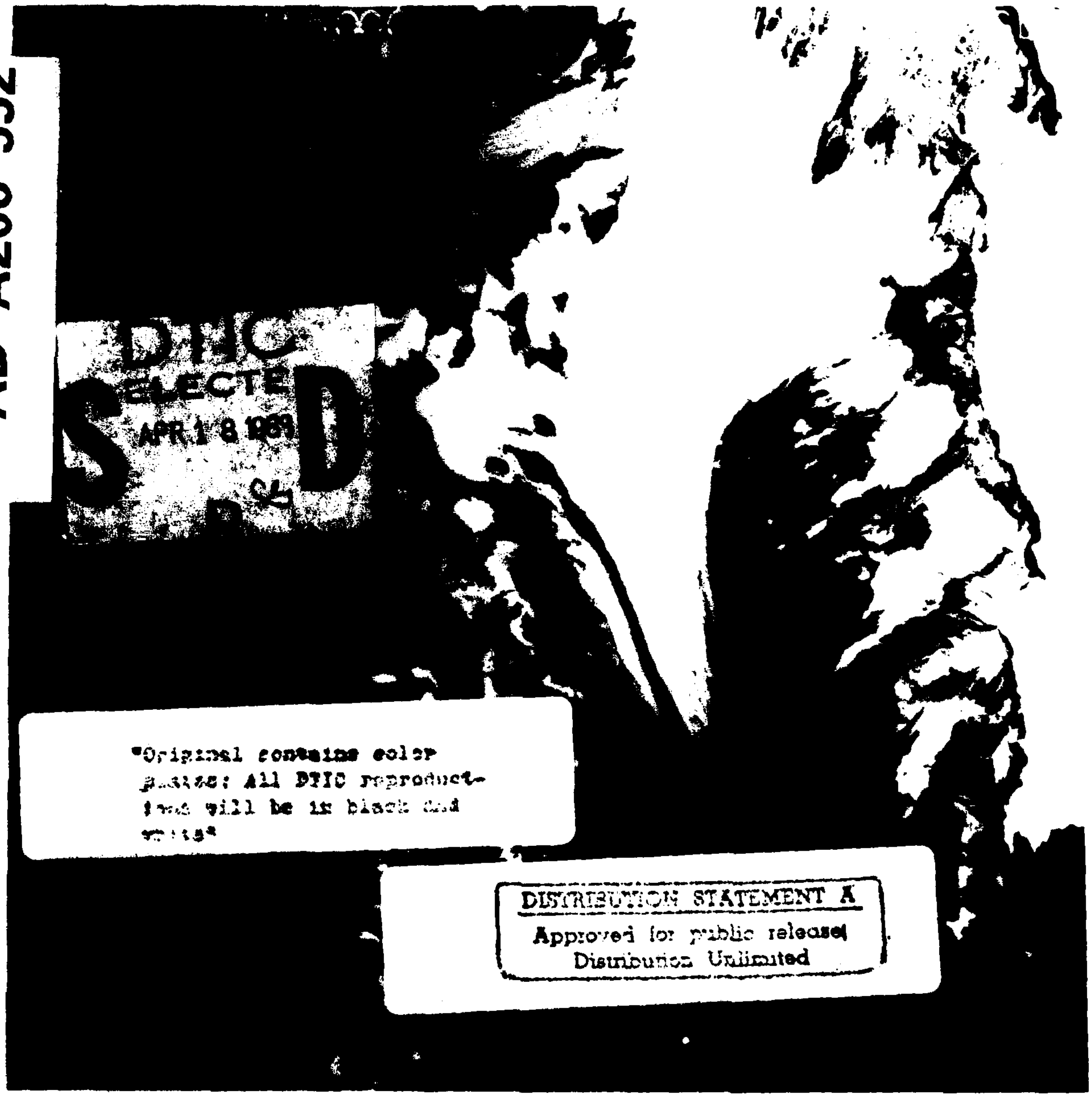



Edited by

**Melvin G. Marcus**
**William J. Reynolds**


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Research Paper No. 1

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This publication is Volume I of a Final Report on climatological and glaciological investigations conducted on and about the West Gulkana Glacier, Alaska, during 1986 and 1987. A second volume, focusing on energy balance climatology and the relationship between glacier behavior and synoptic climate patterns is forthcoming.

# GLACIER AND CLIMATE STUDIES WEST GULKANA GLACIER AND ENVIRONS, ALASKA

FINAL REPORT
OF THE
ARIZONA STATE UNIVERSITY - U.S. MILITARY ACADEMY
WEST GULKANA GLACIER PROJECT
(September, 1988)

VOLUME I



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ARIZONA STATE UNIVERSITY
Department of Geography
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and

UNITED STATES MILITARY ACADEMY
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# THE WEST GULKANA GLACIER PROJECT: 1986-87

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## *INTRODUCTION AND BACKGROUND*

The purpose of the West Gulkana Glacier Project has been to assess Twentieth Century glaciological and climatological trends in the eastern Alaska Range generally and on West Gulkana Glacier specifically. Research objectives include: (1) mapping the glacier at the 5 m contour interval as follow-up to the 1957-58 International Geophysical Year map of West Gulkana glacier; (2) determination of the glacier's annual and 30-year mass balances; (3) energy budget investigations over variable glacier and non-glacier surfaces; (4) meso- and macroscale climatic analyses, especially as they apply to glacier regimens; and (5) short-term (c. 200 year) reconstruction of local glacial geology. This volume provides a preliminary report on much of that research, although a large portion of mass balance and synoptic climatology analysis continues.

The Project is a joint effort of the Department of Geography, Arizona State University and the Department of Geography and Computer Science, U.S. Military Academy. Faculty from both institutions participated, but a major thrust of the program has been directed at research participation by cadet interns and graduate students as well as providing field workshops for undergraduate students.

The West Gulkana Glacier Project had its origins in 1985, when Dr. Melvin G. Marcus of Arizona State University was a

Visiting Professor (January, 1985 - August, 1986) at the Military Academy. COL Gerald E. Galloway, Jr., Deputy Department Head, saw the opportunity to combine Marcus' glaciological and Alaskan interests with summer cadet training at the Army's Northern Warfare Training Center (NWTC), Fort Greely. The NWTC program trains soldiers in alpine and arctic travel and survival. Cadets, as part of their three-week summer training program, practice snow and ice travel techniques on the Gulkana Glacier. In 1985, nine cadets volunteered to remain on the glacier for a five-day glaciological workshop. This was followed by a course in snow and ice processes during the Academy's fall semester. This initial experience, given other factors that follow, led to the realization that a useful research program could be developed.

The Gulkana Glacier is one of three glaciers, the others being the College and West Gulkana, that drain the watershed of Phelan Creek to eventually feed the Delta River (Frontispiece and Figure 1). The Gulkana Glacier had been the focus of intensive studies by University of Alaska glaciologists in the early 1960s (e.g., Mayo, 1963; Mayo and Péwé, 1963; Moores, 1962; Ostenso, Sellman and Péwé, 1965; Reger,1964, 1968; Rutter, 1961, 1965; and Sellman, 1962) and its regimen has since been monitored by the U.S. Geological Survey (e.g., Mayo and Trabant, 1986; Tangborn, et al., 1977; and Meier, et al., 1971).

Neighboring West Gulkana Glacier, although frequently photographed from the air (Mayo, pers. comm., 1986), had not been investigated since 1957-58 when it was one of nine U.S. glaciers mapped at the 5 m contour interval during the International Geophysical Year (American Geographical Society, 1960).

The purpose of that effort had been to provide dated and detailed maps which, when matched with future maps, could be used to determine volume and mass change. The selected glaciers were all relatively small alpine glaciers which were deemed to be representative of various geographic zones in northwestern North America (Canada had a similar program in British Columbia and Alberta). The target glaciers ranged from Blue Glacier on Washington's Olympic Peninsula through Lemon Creek Glacier in

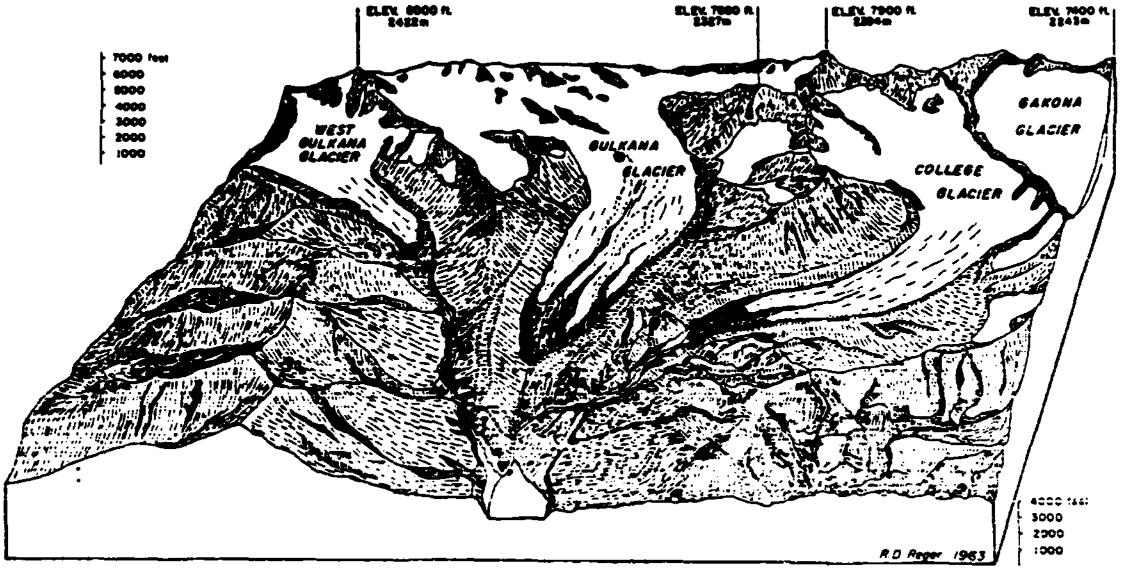


Figure 1. Block diagram view of Gulkana, College, and West Gulkana Glaciers (from Reger, 1968).

southeastern Alaska to six others ranging poleward from the Gulf of Alaska to McCall Glacier in the Brooks Range. West Gulkana Glacier ostensibly provided an index to glacierized terrain lying in the eastern Alaska Range -- astride the divide between the Delta-Tanana lowlands to the north and the Copper River basin to the south.

Three factors were probably paramount in the choice of these glaciers: (1) representation of different glacier-climate regions; (2) the prevailing wisdom at the time, fueled by the advice of the distinguished glaciological pioneer H. W. Ahlmann, that small glaciers provided the best medium for understanding glacier regimen's relationship to climate (Heusser and Marcus, 1964); and (3) accessibility. While the "representativeness" of small glaciers and, to a lesser extent, the geographic zone selections remain arguable, the existing maps are the reality which provide a base on which to determine subsequent mass balance trends.

From the 1985 Gulkana workshop experience, and given the above background, it became clear that nearby West Gulkana

Glacier was ideally situated for the type of follow-up investigation intended by the IGY mapping project. It was accessible in a few hours by foot, in-kind logistical and operational support was available through Ft. Greely, and research could be conducted while also continuing to provide field science experience for USMA Cadets.

A three year research program, including field seasons in 1986 and 1987, was developed. The program was jointly offered by Arizona State University and the U.S. Military Academy, with faculty and student participants from both institutions. Dr. Melvin G. Marcus was Project Director with Dr. Anthony J. Brazel (ASU) and COL William J. Reynolds, Ph.D., as Co-Investigators, the latter directing and coordinating funding and logistics. COL L. Sam Thompson, Ph.D., was in charge of aerial photography and cartography. MAJ Stephen D. Kidder and MAJ Carl O. Horn participated in research and supervised Cadet interns in 1986 and 1987 respectively. MAJ John C. Deal was OIC of workshop Cadets in 1985 and 1986 and participated in the 1987 mass measurement studies. Other participants appear as authors in this volume or in the later ACKNOWLEDGMENTS section. In total, and not counting short-term visitors, the project involved five USMA faculty, two ASU faculty, one Ph.D student, one M.A. student, three Cadet interns, two undergraduate field assistants, and twenty-two Cadet workshop trainees.

The 1986 and 1987 field seasons extended from 12 June to 2 August and 5 May to 6 August respectively. In 1986, the principal research camp was located initially at c. 1,510 m on snow and east of the glacier's central axis (Figure 2). In mid-season, the camp had to be moved down c. 10 m and close to the eastern margin because of slush and sheetwash melting. The new site was almost equally unstable on its base of thin morainic veneer. In 1987, the camp was moved downvalley of the glacier onto a bench mantled by alpine tundra and meadow. Although this required commuting to the glacier and was about 1 1/2 km from the 1986 campsite, the reduction in logistical and operational problems more than compensated for the effort.

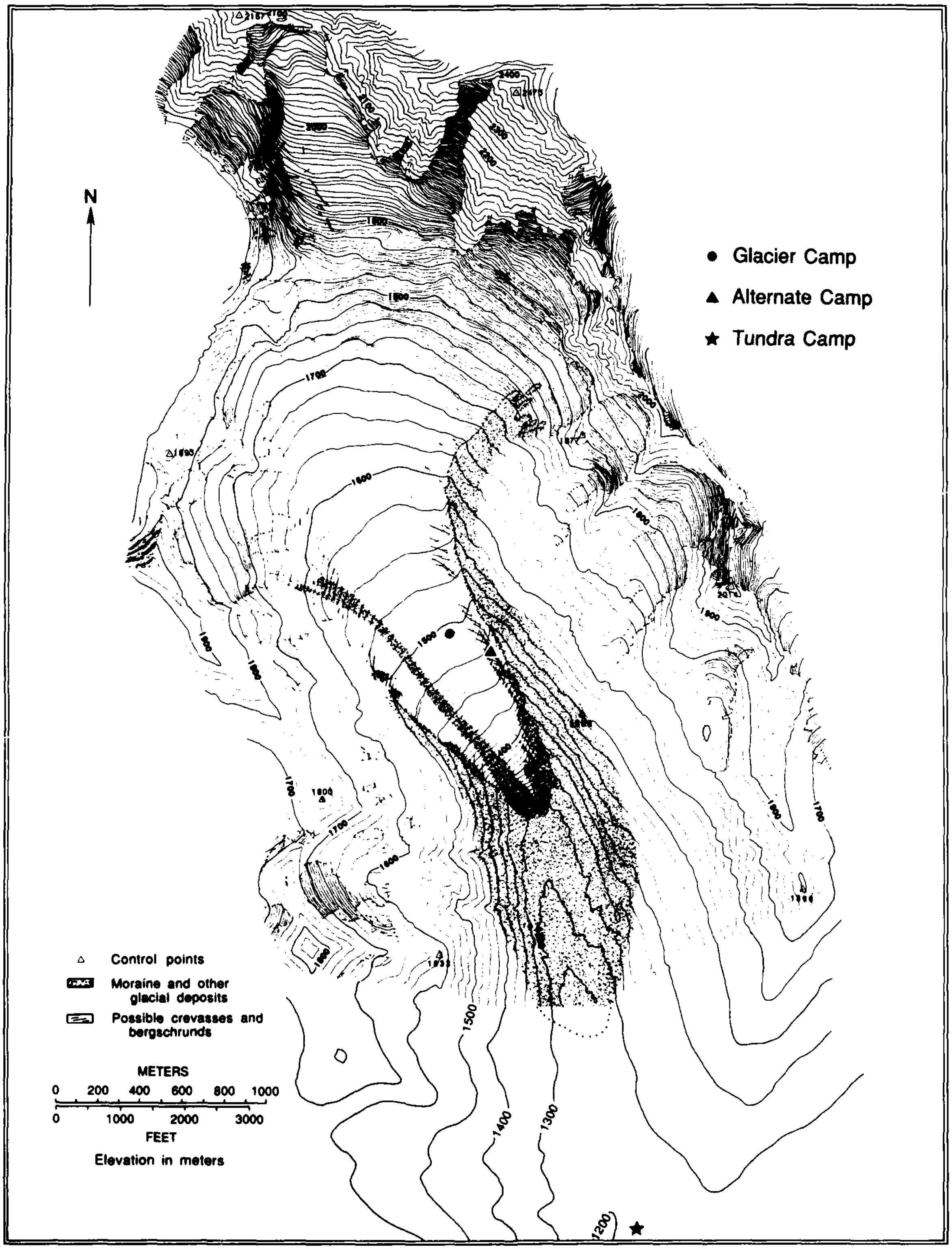


Figure 2. West Gulkana Glacier and environs.

## RELATED INVESTIGATIONS

A variety of glacier-related investigations have been conducted in the West Gulkana area and eastern Alaska Range environs. In addition to the IGY mapping project (American Geographical Society, 1960), ground-based photographs were taken throughout the three-glacier complex in both 1957 and 1959. These reside in the William O.Field collection of photographs, maps, and surveys which trace the fifty-year record of terminal behavior for scores of Alaskan glaciers.

Further afield, regional geology and Quaternary landscapes have been described by, among others, Moffit (1942), Harrison et al. (1983), and Péwé and Reger (1983). The Black Rapids Glacier, subject to rapid advance, has been investigated by Hance (1937), Moffit (1942), Péwé (1951), Geist and Péwé (1957), Post (1960), and Harrison et al. (1975). Additionally, Péwé (1957) has reported on the Castner and Canwell Glaciers. Glacier-climate relationships in the larger region have been investigated by Fahl (1973) and climatic and snow characteristics in the Fort Greely area have been interpreted by Dodd (1962) and Bilello, et al., (1970).

## ACKNOWLEDGEMENTS

The West Gulkana Glacier Project was made possible through the generous help of many individuals and the financial and/or in-kind support of several organizations. We are grateful to all of them, because the project's success was dependent on bringing many pieces of the sponsorship puzzle together. The Association of Graduates, West Point funded the initial 1985 Workshop and another in 1986. Research funds came from the American Geographical Society, Arizona State University, the Army Research Office - Durham, the U.S. Army Cold Regions Research and Engineering Laboratory, and the Dean's Research Fund, West Point. In-kind support was provided by both campus organizations, the Northern Warfare Training Center, the Cold Regions Test Center at Ft. Greely and the Defense Mapping School, Ft. Belvoir. COL Gilbert W. Kirby, Jr. and COL Gerald E. Galloway, Jr., Head and

Deputy Head respectively of the Department of Geography and Computer Science, USMA, provided administrative and moral support. LTC Gerald W. Barnes, Commandant, and the officers and men of the Northern Warfare Training Center provided generous and efficient logistical and operational support. MAJ Wm. Hayes, OIC of helicopter operations, and his crews provided outstanding, timely flying support. Colleen Deal made superb contributions to the field mess. William O. Field, American Geographical Society, supplied both color and black and white ground photography of West Gulkana and Gulkana Glaciers taken in 1957 and 1961. Lawrence R. Mayo and Dennis C. Trabant of U.S.G.S., Fairbanks, provided valuable data and commentary regarding their ongoing studies of Gulkana Glacier. Will Harrison, Carl Benson, and Gerd Wendler of the University of Alaska, Fairbanks, gave generous counsel.

Finally, two persons deserve special mention. William D. Strauss, senior technical advisor for NWTC, coordinated three years of the Project's logistical activity in Alaska as well as participating in field operations at critical times. MAJ John C. Deal, whose major responsibilities involved supervision of cadet trainees in the NWTC school, in all three years gave unstintingly of his own time as a participant in field activities and as our authority on matters involving electronic equipment.

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**CONSTRUCTING A 5-METER CONTOUR MAP AND DETERMINING VOLUMETRIC CHANGE FROM DIGITAL DATA, WEST GULKANA GLACIER, ALASKA**

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## INTRODUCTION

In 1956 the National Academy of Sciences approved a project which consisted of precisely mapping nine carefully selected glaciers. The maps were to form a permanent record of the condition of these glaciers so that at a future date they could be resurveyed and compared. "Continuing surveys, if carried on over a sufficient period of time, would give the history of wastage and accumulation, and the pattern of variation would provide the basis for more satisfactory and more accurate interpretation of the response of these glaciers to meteorological and other factors" (American Geographical Society, 1960).

One of these nine glaciers was the West Gulkana, located in east-central Alaska. The purpose of this paper is (1) to present a new map of West Gulkana Glacier, based on 1986 data; (2) to report how the glacier was precisely mapped at the same 5 m contour interval that was used in 1957; and (3) to demonstrate how volumetric change through time may be calculated using digital data. The new 1986 map is inserted in the rear cover pocket of this volume.

Dr. James B. Case, as part of his master's thesis and doctoral dissertation at The Ohio State University, conducted the original mapping exercise thirty years ago. His undertaking, like that being reported here, was essentially a mapping project rather than a glaciological investigation. However, because sequential mapping is so conducive to volumetric comparisons, this type of study is of unique value to glaciologists.

Dr. Case realized in 1956 that it was not necessary to know the exact location and absolute orientation of each glacier. Therefore, he carefully established for each glacier a survey network that was rigid and precise in a relative sense. Using a Wild P-30 theodolite he occupied eight control points in the vicinity of the West Gulkana Glacier. Two other points, although not occupied, were triangulated from several locations and used as vertical control during the aerial triangulation/plotting phase.

## PROCEDURE

Using Dr. Case's carefully preserved survey data, the original glass diapositives (taken by the United States Navy Heavy Photographic Squadron 61) and the American Geographical Society's map, the original control points were recovered. While the original study was limited to triangulation from a 200 m baseline, the most recent group, enjoying the luxury of an electronic distance measuring device (DM 60) and a Wild T-2 theodolite, were able to establish a baseline of nearly two kilometers. As evidence of the precision of the original survey, the electronically measured 1,783.5 m distance from control points "Shirley" to "Velta" varied by only 30 cm from the triangulated distance of Dr. Case.

A flight line and mission plan were prepared independently of any previous work. The conclusions were nearly identical: a flight line running NW to SE, four 60% overlapping photographs, and a photographic scale of approximately 1:27,000. Air Photo Tech, INC., an Alaskan based company, flew the mission with a Zeiss Jena MRB camera employing a Lamegon PI lens (focal length of 151.964). VEP Associates of Caldwell, New Jersey, working from the glass diapositives supplied by Air Photo Tech, formed the models and densified the control using a DSR-11 Analytical Stereorestitution Instrument. The ground coordinates were computed using Kern's version of Shut's polynomial solution. The DSR-11 was used to digitize the contours and morainic and other glacial features -- gathering a digit every 0.05 inches at the publication scale of 1:10,000. Inked contours were drawn on mylar by a Calcomp 1076 Belt Plotter being driven by computer assisted drafting software on a Microvax II minicomputer at a Tektronix 4111 Graphic Workstation. The contour lines, outline of the glacier, prominent ice fields, and obvious morainic deposits, as in the original, were plotted at a scale of 1:10,000 with a 5 m contour interval. Ice-free land masses were plotted at a contour interval of 25 m.

The inked manuscript was photographically superimposed on scribe and peel-coat materials by the Department of Graphic Arts, Defense Mapping School. As part of a classroom training exercise, they further scribed the contours, peeled ice and moraine locations, prepared lettering, made the plates, and printed the final map.

## GLACIER CHANGE: 1957-1986

An analysis of the change in glacier volume was conducted using digital data taken from the two maps. The contour lines of the 1957 map, and those based on the photographs gathered in 1986, were digitized using a Numonics Model 2200 table digitizer connected to an IBM PC/AT microcomputer. The operator carefully produced a stream of x and y coordinates (one every 0.05 inch) by tracing the contours with a four button cursor equipped with a well-defined crosshair. The digitizing software interactively prompted the operator to provide a "line tag" which, in this case, consisted of the elevation of each contour line. This data was considered to be "irregular", i.e., it wasn't laid out in a uniformly drawn matrix with each grid intersection having an unique x,y,z value.

The software used to manipulate and display the data was UNIRAS, the Universal Raster System, produced by an European company working out of Boston, MA. UNIRAS is a high-level application software package comprised of several subroutines which may be called from a menu. Multi-color, 2,3, and 4D plots, and rotatable perspective views may be produced on demand from

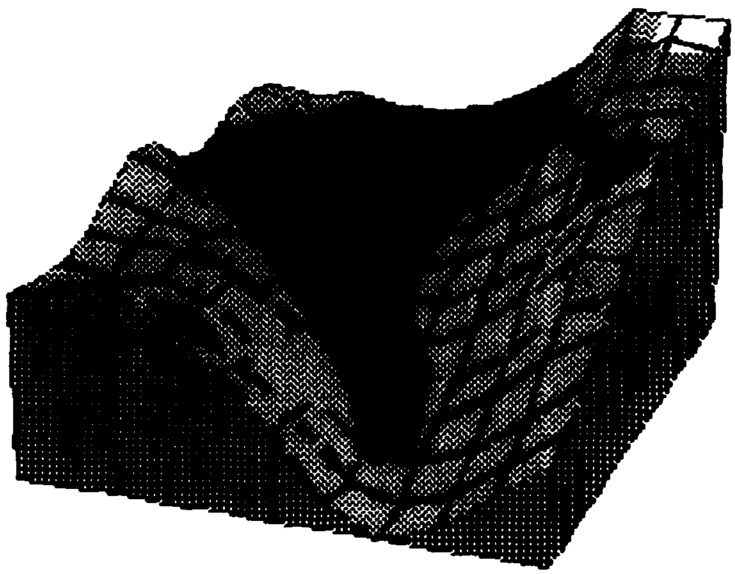

Figure 1. 1957 computer-generated, three-dimensional view of West Gulkana Glacier.

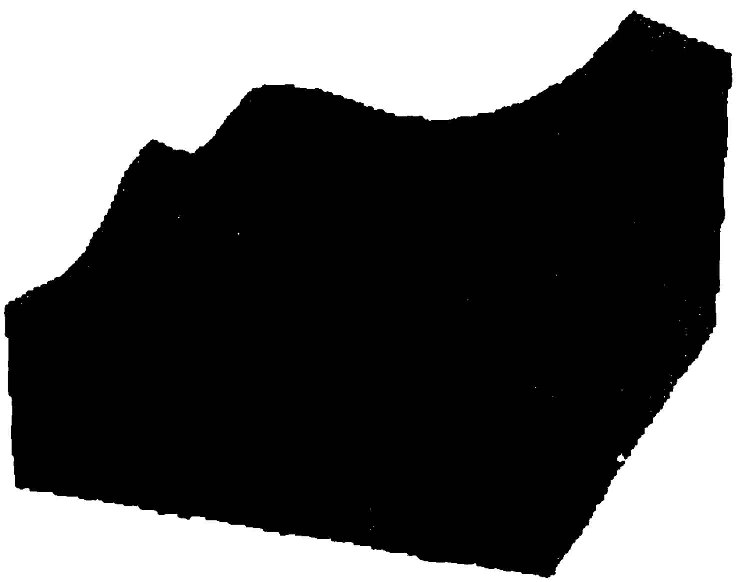

Figure 2. 1986 computer-generated, three-dimensional view of West Gulkana Glacier.

this sophisticated device- independent software (See Figures 1 and 2).

UNIRAS can accept the data in any format as long as it is presented as an x, y and z value on one line. Although data in this format may be displayed as discrete points, in order to produce contour line maps or continuous color displays of higher dimensions, the data must be "regularized." This is accomplished with the menu command "INTERP," which offers the user a wide range of interpolation choices and other options. The selected quadratic and distance weighting methods computed an average z-value for each of the several thousand evenly spaced, square grid cells that it mathematically overlayed onto the glacial area (UNIRAS 1985). The positional accuracy of a datapoint is limited to being equal to or less than the size of the cell in as much as the datapoints are assumed to be placed in the center of the gridcell (UNIRAS 1985).

Obviously, the number of irregular data points and the density of the gridcells play roles in the computed mathematical shape of the area and the subsequent volumetric computations. The contour lines on both the 1957 and 1987 maps are generally smooth, evenly-distributed, laterally-drawn curves separated by 1-4 mm at map scale. This translates to a separation of 10-40 m at ground scale which corresponds nicely with the digitizing frequency of 0.05 in at the tablet, or 12.7 m on the ground. The area of concern on the ground was 2540 m by 3048 m (10 in by 12 in at map scale). Several gridcell dimensions were tried with a size of 100 X 120 being chosen. This resulted in each cell on the ground being 25.4 m on a side. Considering that the slope of the glacier was generally smooth, it is believed that little error resulted from these interpolation techniques. Even if a systematic error was introduced, it would be approximately the same for both the 1957 and 1987 maps. This means that the resulting difference in volume, computed by comparing the sums of the volumes of the many columns, would be generally independent of this error and, thereby, precise in a relative sense.

## VOLUME COMPUTATIONS

A basic problem facing glaciologists is to determine if a glacier has exhibited mass increase or decrease after a specified time. There are four methods commonly used to determine mass balance: direct measurement (snow pits, cores, layer determination, etc.); volume change determined from contour line comparison of two maps; hydrological monitoring (stream gauges, evaporation estimation, etc.); and snow line measurement (Patterson, 1983). A fifth method, basically a variant of the contour line method, uses digitized coordinate data.

Three dimensional terrain views are generally based on the plotting of very small columns (see Figure 3). The columns have an x and y location at the four corners of their base and a corresponding z, or elevation. A program was written to average the matrix values denoting the elevations of the four corners of each grid cell in a given UNIRAS 3D image, and then multiply it times the area of each cell. The sum of the volume of the individual columns comprises the total volume of the land and ice at one time. The difference in these totals represents the change in volume over 30 years which is realistically the result of a change in the glacier ice (over this geologically short period there would be no noticeable change in the very hard bed rock surrounding the glacier). It should be noted that the photographs from both the 1956 and 1986 missions (which permitted the publishing of the maps one year later) were acquired at the end of the summer, prior to the winter snows.

Summing the volumes of 12,000 gridcells (i.e. a grid of 100 X 120) and comparing the cumulative totals for 1957 and 1986 resulted in a mass loss of 42,064,100 $m^3$ or 35,754,485 $m^3$, based on a mean glacier density of 0.85. This translates into the visually apparent c. 350 m recession of the terminus and general lowering of the ice mass on the valley walls of approximately 20m.

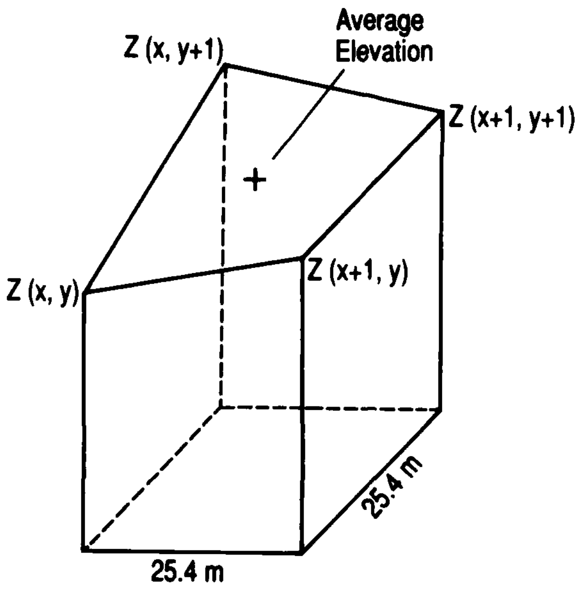


Figure 3. Volume of each column is the average Z value times the area of the base. Total volume for each period (1957 and 1986) is the sum of 12,000 columns.

## CONCLUSIONS

The 1986 5 m contour interval map of the West Gulkana Glacier, taken with the IGY map, provides a 29-year record of glacier history and permits meaningful comparison with the climatic record. Further, it provides a base on which to determine future mass balance variations. It is envisioned that this 1:10,000 map sheet will not only serve as a permanent record of what has occurred over the past thirty years, but will permit the meaningful comparison of this digital data method to other more established methods. For certain, the legacy envisioned by the National Academy of Sciences has been realized; a carefully selected glacier has been studied in detail, this being only one of several reports reflecting the knowledge gained.

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# DETERMINATION OF 1957-1986 MASS BALANCE OF WEST GULKANA GLACIER, ALASKA, BY COMPARISON OF TOPOGRAPHIC MAPS

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Glacier mass balance may be determined in a number of ways. For periods of several years or decades, the method of measuring volumetric change by comparison of topographic maps is especially effective. This technique was developed by Finsterwalder (1960) to examine changes in the volume of several European glaciers and has been used in North America to determine, for example, changes of Salmon Glacier in the British Columbia Coast Range (Haumann, 1960) and Lemon Creek Glacier in the Juneau Ice Field, Alaska (Marcus, 1964). In the method as initially developed, comparative methods depended on hand planimetry; more recently, it has become possible to utilize digital data generated from the maps. This paper compares the two methods as used to determine the 1957-1986 mass balance of West Gulkana Glacier, Alaska.

## THE PLANIMETRIC METHOD

The planimetric method requires two topographic maps of the same scale and contour interval. For West Gulkana Glacier, the original map was constructed from 1957 aerial photography and surveys (American Geographical Society, 1960) as part of the United States' effort to map nine small "representative glaciers" in Washington State and Alaska during the International Geophysical Year (IGY). This map was published at a scale of 1:10,000 with a 5-m contour interval on ice and snow surfaces and a 25-m interval for surrounding terrain. The second (overlay) map was based on 1986 aerial photography, drafted at the same scale and contour interval, and is described elsewhere in this volume by Thompson and Smith.

Contours of the newer map are drawn onto tracing paper or a similarly transparent material. This map is then superimposed upon the original map, allowing comparison of the changes in contour line location and, thereby, setting up for calculation of ice elevations and areal extent (Figure 1). Contour lines and areas are planimetered to provide solutions as described below.

The change in the height of the ice during the intervening period between map surveys is given by the calculation

$$dh = h\left(\left( A_1 + A_2\right) / \left(A_1 + A_2\right)\right), \tag{1}$$

where $A_1$ is that area which is enclosed by the consecutive contour lines of the original map and the glacier margins of the new map, $A_2$ is that area between consecutive contour lines and glacier margins of the new map, $A_1$ is the area delineated by the displacement of the same contour line and the new glacier margin at the upper end of the zone being measured, and $A_2$ is the area delineated by the displacement of the same contour line and the new glacier margin at the lower end of the zone being measured. h is the contour interval.

Volumetric ice change, dV, (loss or gain) is determined by

$$dV = A_m \, (dh) \tag{2}$$

where

$$A_m = A'_1 + A_2 \;\; / \; 2 \tag{3}$$

and $A'_1$ is the area enclosed by the original map's consecutive contours and the old glacier margins (Haumann, 1960).

This technique allows for the determination of: (1) the gross change in ice mass from the original survey to the follow-up; (2) the average annual mass balance for the years between map construction; (3) the change in average equilibrium line altitude; and (4) down glacier propagation of kinematic waves. A major disadvantage of this method is the inability to determine annual fluctuations in glacier mass balance as well as rates of annual accumulation and ablation.

Calculations revealed major changes of West Gulkana Glacier

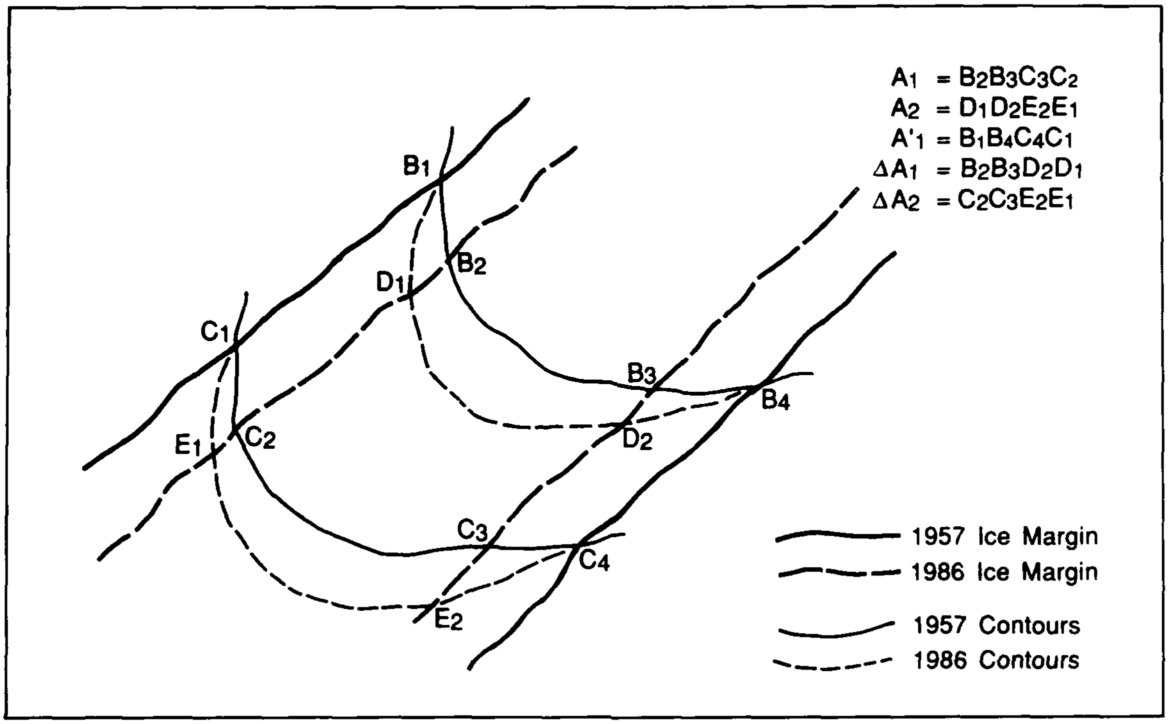


Figure 1. Contour line displacement on a retreating glacier.

during the 29-year period. Changes in thickness (dh) and volume of ice (dV) are presented in Table 1 for every 100 m interval. Water-equivalent (mass) values ($dV_w$) are also given based on an average density of 0.85.

As expected, the most pronounced loss of ice volume and extent occurred at the lowest elevations along the glacier snout. Ablation below the 1,700 m contour accounted for 93 percent of the total volumetric loss of the glacier from 1957 to 1986, while the terminus appears to have retreated approximately 350 m. Interestingly the glacier has sustained a net mass gain between 1,900 and 2,100 m. This represents an average increase of about 3.25 m ice thickness and a volume increase of c. 2.4 x $10^6$ $m^3$. Ice losses occur again above the 2,100 m contour line, but at a much lower rate than the lower elevations of the glacier. Ice above the 2,100 m contour is in a couloir of Institute Peak and is probably not a significant factor in the glacier's mass budget. The volume increase between 1,900 and 2,100 m may be a kinematic wave. A similar thickening has been detected on the neighboring Gulkana Glacier and is believed by Mayo (1986, pers. comm.) to be a kinematic wave.

## DIGITAL DATA METHOD

The volume changes from 1957 to 1986 were also determined by digitizing and geometric manipulation of that data. Both 1957 and 1986 maps were digitized so that four data columns were created -- an "x" coordinate, a "y" coordinate and two "z" coordinates (one with 1957 elevations and the other with 1986 elevations). The maps were then compared using the GRIDZO program. GRIDZO (1986) is a common engineering geology program primarily used to determine cut-and-fill volumes at construction sites.

Gridzo interpolates a uniform grid from the digitized control point data. The program is well suited to the task of comparative volumes, as it has the ability to subtract the 1986 "z" values from the 1957 "z" values in order to create a third output file of elevation change. Knowing the area for each grid cell, this elevation change can be easily transformed into volumetric change. This volume change is then the twenty-nine year net balance for the glacier.

GRIDZO has several different algorithms which it may use to interpolate a grid from the control points. The calculated volumetric change from each algorithm was surprisingly consistent and ranged from 62.2 to 64.5 x $10^6$ $m^3$ of ice loss or 52.87 to 54.83 x $10^6$ $m^3$ water equivalent. This represents up to 88 percent of the value determined by the planimetric method. The discrepancy between the two methods is explained by closer examination of how the computer interprets the change in the "z" values. Both maps were digitized to include both ice areas and non-ice areas. Naturally, only the "z"

**TABLE 1**
**VOLUME AND ICE THICKNESS CHANGES IN WEST GULKANA GLACIER, ALASKA: 1957 TO 1986**

| Contour Interval (Meters) | dh (Meters) | dV ($\times 10^6$ $m^3$) | $dV_w$ ($\times 10^6$ $m^3$) |
|---|---|---|---|
| 1325 - 1425 | -33.00 | -11.4809* | - 9.7588 |
| 1425 - 1525 | -50.66 | -19.4630 | -16.5436 |
| 1525 - 1625 | -33.99 | -21.0125 | -17.8606 |
| 1625 - 1725 | -20.82 | -16.2427 | -13.8063 |
| 1725 - 1825 | - 7.57 | - 4.4258 | - 3.7619 |
| 1825 - 1925 | - 2.13 | - 2.4316 | - 2.0669 |
| 1925 - 2025 | + 3.80 | + 1.8540 | + 1.5759 |
| 2025 - 2125 | + 2.73 | + 0.5736 | + 0.4876 |
| 2125 - 2225 | - 7.17 | - 0.1563 | - 0.1329 |
| 2225 - 2325 | -16.64 | - 0.5016 | - 0.4264 |
| 2325 - 2350 (note: 25 m interval) | - 5.88 | - 0.0441 | - 0.0375 |
| Total | | -73.3309 | -62.3313 |

* Calculated by direct volume integration

values on the ice should have shown a net change between the two maps, but GRIDZO does not act precisely on the boundary between glacierized and non-glacierized parts of the map; thus, it interpolates the edge of the ice mass to gradually phase into the region of non-ice where there is no change in "z" values. This creates a boundary error whereby GRIDZO "sees" more ice than is actually present, leading to the discrepancy between the two methods. Furthermore, the error is not constant but will vary as a function of boundary location relative to the digitizing grid.

The boundary error problem will be compounded when a greater area is digitized. This may be part of the explanation behind the even lower value of ice volume loss determined by Thompson and Smith who digitized the glacier and all snow/ice masses appearing on both maps. While they did not employ GRIDZO, they did use an interpolation program which would presumably experience a similar boundary problem to that described above. Another explanation to their lower value may be the greater area which they digitized above the 1900 m elevation. Snow and ice masses above this elevation may have experienced a thickening analogous to that seen on the glacier leading to a reduced figure for the overall glacier/snow/ice mass loss of the quadrant.

## CONCLUSIONS

The West Gulkana Glacier has experienced an extremely negative budget for the past 29 years. Planimetric method calculations indicate that the glacier has lost 73.3 x $10^6$ $m^3$ of ice volume or 62.3 x 106 m3 water equivalent. This represents an average annual loss of 2.5 x 106 m3 (2.1 x $10^6$ $m^3$ water equivalent).

Volumetric loss was also determined by digitizing both the 1957 and 1986 maps of the glacier. This digital data method produced results which were approximately 88 percent of the values determined by the planimetric method. Problems occur when the algorithm used to calculate the volume difference approach the edge of the ice area. These boundary problems appear to be the result of program interpolation between those areas which show "z" axis change (ice and snow) and those that do not (everywhere else). The result is an increase in the amount of ice area observed by the program, and a decrease in computed net volume loss compared to the competing planimetric method. While the digital data method is a much faster way to determine volume change, it would appear that the planimetric method is superior; at least until a program can be found (or written) that addresses the ice edge or boundary interpolation problem.

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# TWO-YEAR MASS BALANCE OF WEST GULKANA GLACIER, ALASKA

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## INTRODUCTION

The mass balance of a glacier may be measured either by indirect or direct methods. Indirect methods are much less costly and time consuming. These methods include, for example, comparison of topographic maps (see Chambers; Thompson and Smith; this volume), photographic surveys of snow-line elevation on the glacier at the end of the ablation season (Marcus, 1964) and by remote sensing technology (Krenke and Menshutin, 1987). The disadvantage to the above techniques are in the results obtained. At best, these methods provide only approximations of the glacier's annual mass balance and then only if direct measurement has been previously computed.

Direct measurement, while both costly and time consuming, provides the only reliable means of annual mass balance determination. Direct mass balance measurements were completed on the West Gulkana Glacier during the summer of 1986 and the spring and summer of 1987.

## METHODOLOGY

The mass balance of a glacier is determined by measuring the depth and density of the previous winter (accumulation season) snowpack on the glacier in late spring or early summer and following the rate and amount of snow/ice melt through the summer ablation season. The "mass balance year" is defined as the period from the beginning of the previous accumulation season to the end of the following ablation season (Meier, 1962; I.A.S.H., 1968). This period of time is not necessarily 365 days. It may be less than 365 days if the ablation season is short and/or the fall snows come early, or longer if the opposite is true.

Detailed measurements of the glacier surface are necessary to ascertain the amount of increase or decrease in the mass balance of a glacier. The mass balance of the West Gulkana Glacier was determined by measuring snow depth and density throughout the summer of 1986 and spring and summer, 1987 (Figure 1). Following Ostrem and Stanley (1969), snow depth was measured (from the terminus) approximately every 100 m longitudinally (north-south) up the center of the glacier to an elevation of 1800 m. Four snowpits were excavated at different elevations ("Low Pit", 1415 m; "Middle Pit", 1500 m; "High Pit", 1560 m; "Cirque Pit", 1645 m) to provide snow density information. Additional snow depth measurements were made approximately every 100 m from each snowpit latitudinally (east-west) to the sides of the glacier.

Glacier ice was exposed first at the terminus and the snowline moved up glacier as the ablation season progressed. Holes were drilled into the ice and stakes inserted to assess the ice loss after an area became free of snow. The distance from the top of the stake to the ice surface was measured and re-measured periodically. Differences between the two measurements provided depth of ice ablation. The mass balance of the West Gulkana Glacier was determined by dividing the glacier into four areas, each centered around a snow pit location. The mass balance was summarized from the more detailed calculations of each sector. Results presented herein are preliminary.

Mass balance measurements on the West Gulkana Glacier were recorded regularly from 26 June to 25 July 1986. Two additional site measurements were taken on 12 September 1986 to determine the amount of ice loss after 25 July. The glacier was reoccupied on 10 May 1987. Regular mass balance measurements resumed and continued until 25 July 1987. It is probable that the initial readings in May represent the greatest accumulation of the winter season. Snowfalls continue in this region into April. Any snow melt at the surface would most likely be refrozen at depth within

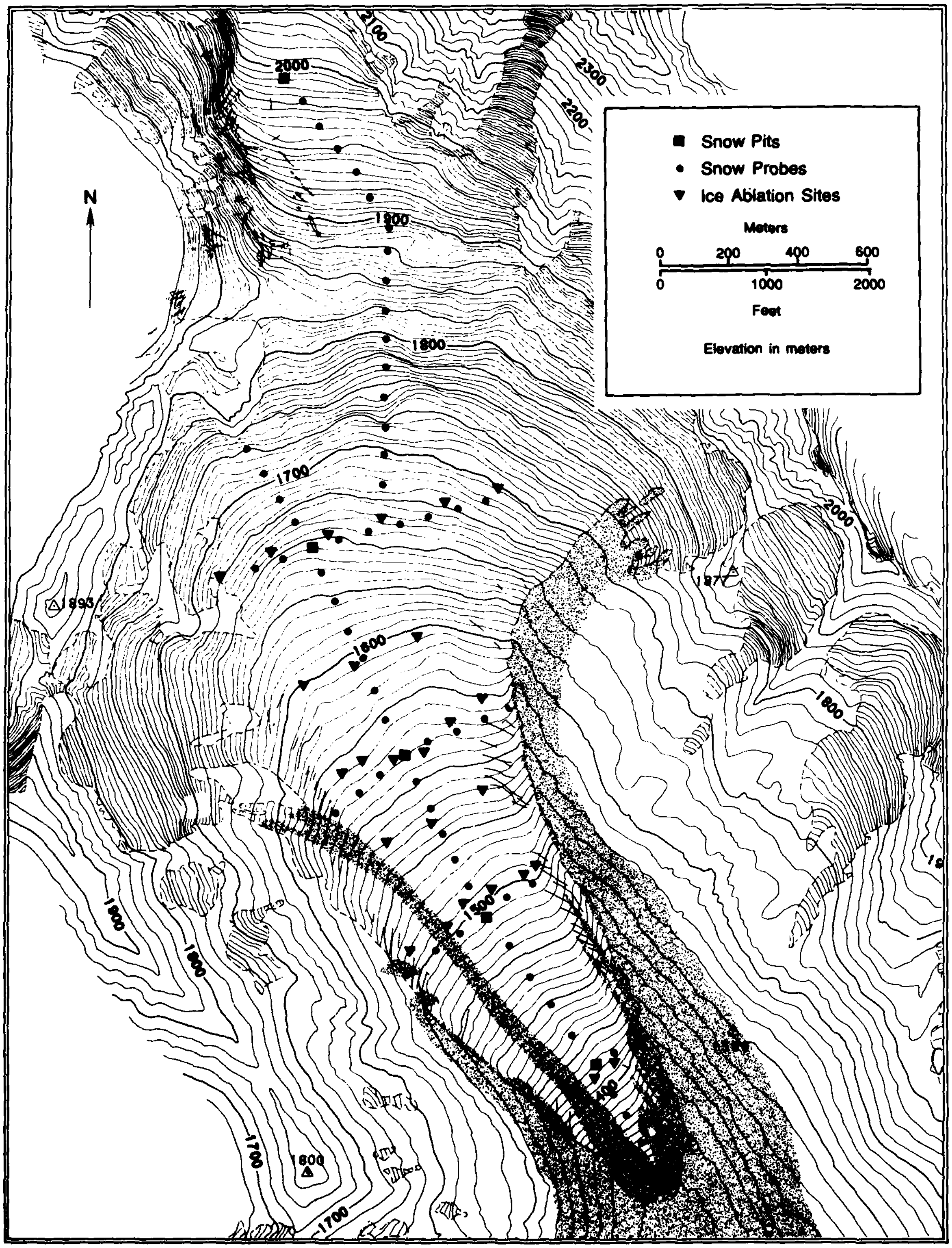


Figure 1. West Gulkana Glacier.

the snowpack, resulting in little runoff and mass loss.

## 1985-1986 ANNUAL BALANCE

Mass balance measurements commenced on 26 June 1986. At that time, snow depth on the glacier ranged from a minimum of 0.59 m (near the glacier terminus) to 2.68 m (approximately 100 m west of "Cirque" snowpit). Glacial ice first appeared near the terminus on 2 July. The mean snowline was at the "Low" snowpit elevation on 4 July, the "Middle" snowpit site on 8 July, the "High" snowpit on 19 July, and at the "Cirque" site on 22 July--an elevation rise to 230 m in 22 days or 10.5 m/day. Most of the glacier was free of snow when the team left on 25 July, indicating a severely negative mass balance for the 1986 year (Figure 2).

TABLE 1

1985-86 AND 1986-87 ANNUAL MASS BALANCE FOR WEST GULKANA GLACIER

| Location | Area ($m^2$) | $H_2O$ Equiv. (m) | | Volume Change ($m^3$) | |
|---|---|---|---|---|---|
| | | 1986 | 1987 | 1986 | 1987 |
| Low Pit | 209,000 | -1.22 | -1.14 | -254,980 | -238,260 |
| Middle Pit | 302,000 | -1.12 | -0.78 | -338,240 | -235,560 |
| High Pit | 433,000 | -0.66 | +0.33 | -285,780 | +142,890 |
| Cirque Pit | 1,355,000 | -0.69 | -0.48 | -934,950 | -650,400 |
| | | | Total | -1,813,950 | -981,330 |

Preliminary results (Table 1) show that the area surrounding the Low snowpit site (210,000 $m^2$) lost an average of 1.22 m of $H_2O$ equivalent, resulting in a volumetric loss of 254,980 $m^3$. The Middle snowpit area (300,000 $m^2$) showed a loss of 1.12 m of $H_2O$ equivalent, and a volumetric loss of 338,240 $m^3$. $H_2O$ equivalent loss in the High snowpit area (433,000 $m^2$) was only

0.66 m or roughly half of the loss experienced by the lower elevations. This represented a volumetric loss of 285,780 $m^3$. The $H_2O$ equivalent loss in the area of the Cirque snowpit (1,355,000 $m^2$) paralleled that of the High snowpit region. Here, 0.69 m of $H_2O$ equivalent ablated, or 934,950 $m^3$ of volume. Nowhere on the main body of the glacier was an increase in mass observed. In total, the West Gulkana Glacier lost over $1.8 \times 10^6$ $m^3$ of $H_2O$ equivalent mass during the 1985-1986 budget year.

## 1986-1987 ANNUAL BALANCE

Snow began to fall on the glacier (and remained on the surface) during the second week of September, 1986, effectively marking the end of the 1985-86 and the beginning of the 1986-87 balance years. The glacier was reoccupied and measurements restarted on 10 May. On that date, the snowpack varied from a minimum depth of 1.55 m near the terminus to 4.3 m approximately 300 m west of the High snowpit location. No measurements were completed above this site due to adverse weather conditions; it is probable that the maximum snowpack depth was in excess of 4.3m.

Subsequent snow probes revealed that a lobe of deep snowpack existed in a southwest to northeast line centered in the vicinity of the High snowpit. There is good evidence to believe that this additional snow came from avalanches originating on Institute Peak to the northeast and the ridges to the west of the glacier. Residual snow, derivative of the avalanche zones, is apparent in a mid-July photograph (Figure 3).

It is believed that this type of avalanche contribution to mass balance is not usual for West Gulkana Glacier. Ordinarily, as in 1985-86, the snowpack on surrounding peaks and slopes develops gradually through the accumulation season and a large proportion of that snow remains stabilized on the valley walls into and through the summer season. In 1986-87, however, deep winter snowfall was relatively light and very heavy snow fell in April just before the onset of ablation. This lead to a dense, unstable snowpack which avalanched almost in its entirety.

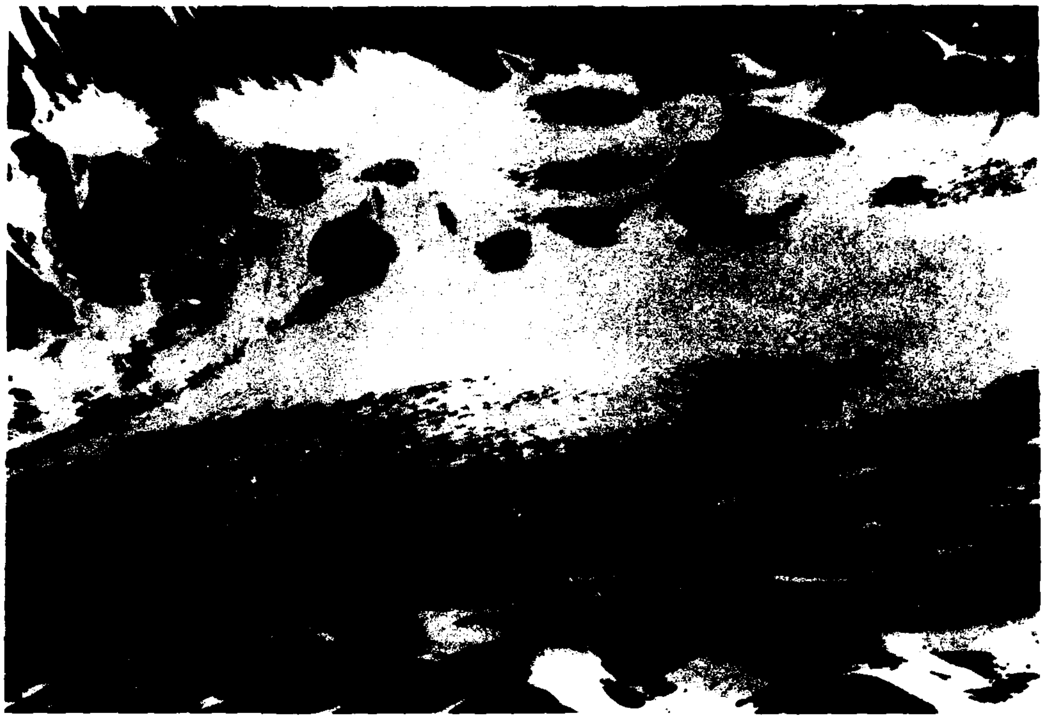

Figure 2. West Gulkana Glacier, late July, 1986. Practically all 1985-86 accumulation has ablated.

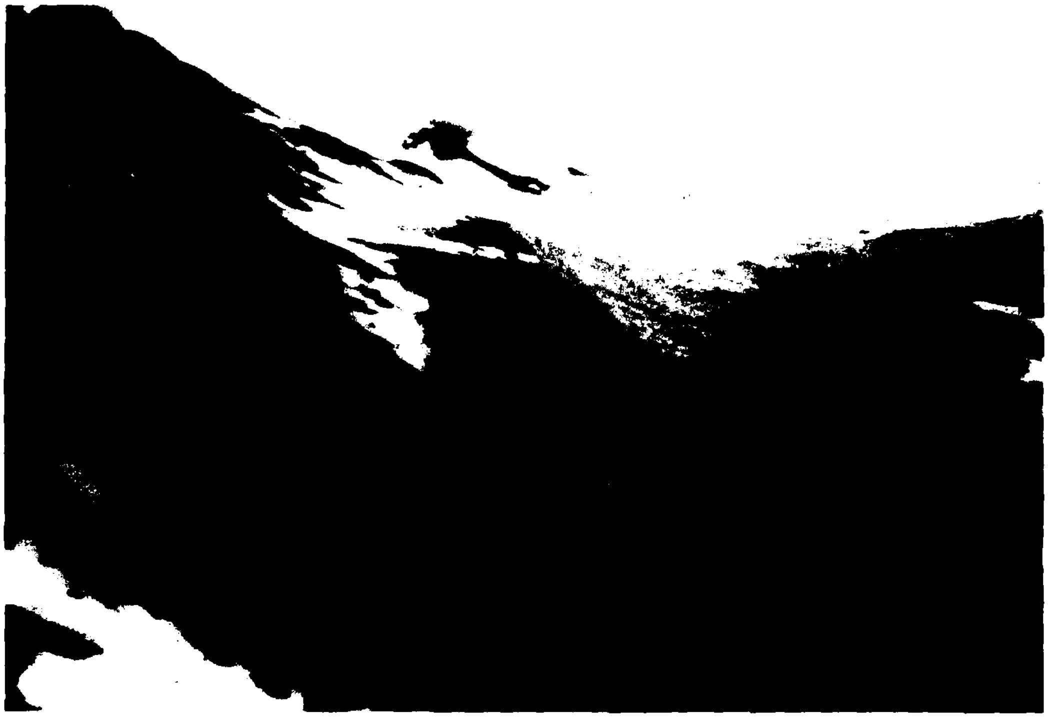

Figure 3. West Gulkana Glacier, late July, 1987. Note residual snow in spring avalanche areas.

Field evidence for this includes the fact that valley wall névé disappeared by the end of June, whereas it remained into August during the 1985-86 budget year. Also, residual avalanche debris were present throughout the summer in the glacier outwash zone and lower stream-cut canyons; no snow was apparent after July 1 in 1986.

Similar to the previous year, glacial ice was first exposed at the glacier terminus on 1 July, 1987. Unlike 1986, the snowline did not reach the Low snowpit location until 9 July and the Middle snowpit area was not free of snow until 19 July. Because of the avalanche lobe, the High snowpit area was covered with snow the entire summer of 1987, and only those areas outside the avalanche path were free of snow in the Cirque pit area after 24 July. The additional input of snow from avalanching therefore played a significant role in moderating the glacier's negative budget (Figure 2).

The Low snowpit area lost an average of 1.14 m of $H_2O$ equivalent during the 1987 ablation season. This represents a volume loss of 238,260 $m^3$. A water equivalent of 0.78 m vertical loss and 235,560 $m^3$ was determined for the Middle snowpit region. The avalanche lobe contributed to the positive balance value found in the area surrounding the High snowpit. A water gain of 0.33 m or 142,890 $m^3$ volume were added to this sector of the glacier. Losses once again exceeded gains in the Cirque pit area. Here, 0.48 m $H_2O$ equivalent were lost, representing a volumetric loss of 650,400 $m^3$.

A total of $0.98 \times 10^6$ $m^3$ of $H_2O$ equivalent were lost from the West Gulkana Glacier during the 1987 balance year. While this value is almost half that seen the previous year, it still shows a glacier with a highly negative budget.

## SUMMARY

The results of the two balance years, 1985-86 and 1986-87, which are summarized in Table 1, reveal mass water loss below the mean negative 29-year mass balance rate of $2.1 \times 10^6$ $m^3$ (see Chambers, this volume). The 1985-86 loss is 86 percent of the long term mean; 1986-87 losses are only 47 percent of that mean. It has already been demonstrated that late accumulation season avalanching may have influenced the 1986-87 result. Also, the fact that the glacier has diminished in area by c. 13 percent over three decades has to some degree altered its accumulation-ablation potential. It must be recognized, finally, that annual climatic fluctuations probably remain the major causative factor. These are currently being analyzed for inclusion in Volume II of the West Gulkana Glacier Project Report.

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# RECENT GLACIATION OF WEST GULKANA GLACIER, ALASKA

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## INTRODUCTION

The West Gulkana Glacier, Alaska, has undergone considerable thinning and retreat since the middle 1800s. The extent of the ice loss and the years which marked the glacier's rate of most rapid deterioration have not been detailed previously. Although some research has been done reconstructing advances and retreats of glaciers in the region, neighboring glaciers have received the most attention. Reger (1968) provided a recent chronology for the moraines of Gulkana and College Glaciers; work on other glaciers in the area are cited by Marcus and Reynolds (this volume). This paper provides a preliminary summary of the recent history of West Gulkana Glacier.

Reconstruction of the glacier's history over the past 150 years can be interpreted by reference to three periods: 1830-1910, 1911-1957, and 1957-1986. Except for 1830, the years marking the beginning and end of each period represent years in which the glacier's terminus location is known and correspond to the photographic record. The year 1830 marks the estimated year of the glacier's last advance. The first known photograph of the glacier was taken in 1910; the glacier was subsequently photographed in 1957, 1959, and, most recently, 1986. The photography and field work, taken in conjunction with Reger's (1968) study of nearby Gulkana and College Glaciers, allow comparative reconstruction of West Gulkana Glacier's recent history.

Locations for terminus positions post-dating 1910 were mapped based upon interpretation of ground and aerial photography

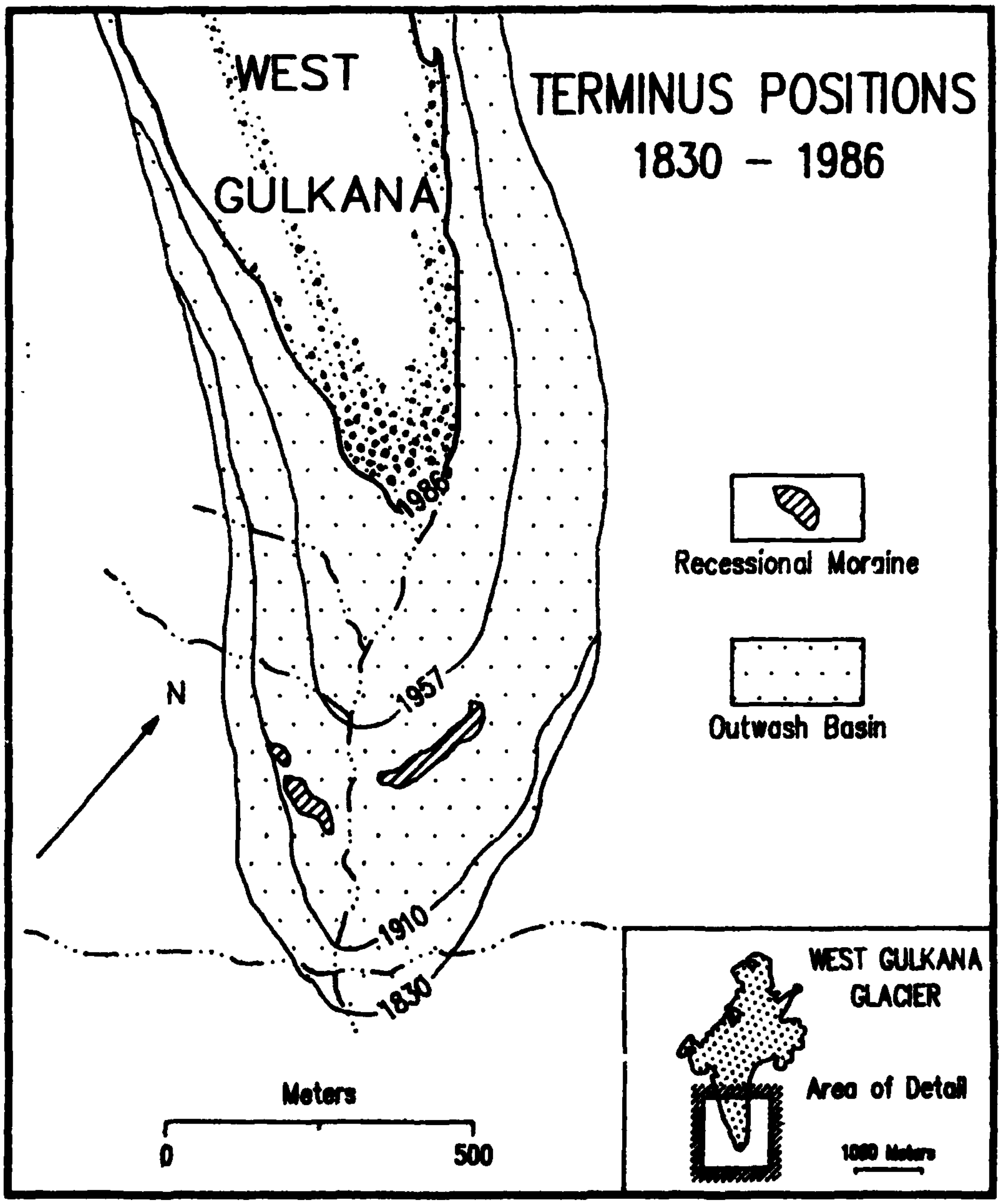


Figure 1. West Gulkana terminus and pro-glacial zone depicting approximate terminal positions over the past 200 years (map by M.E. Hoffpauir).

taken in 1910, 1957, and 1986. Accurate placement of terminus positions (Figure 1) was accomplished (1) by analysis of visible trim lines along valley walls; (2) measurements of distances to glacial features from known sites such as streams and depressions; and (3) relating ice position to recognizable moraines. Locations for terminus positions pre-dating 1910 were established during field work in summer, 1986, by comparing moraine deposits of West Gulkana to College and Gulkana Glaciers, and using Reger's 1968 study to assign correlative dates. Field work involved analysis of glacial deposits around and downvalley of the glacier's terminus. Relative dating of these deposits was accomplished by inspecting degree of weathering, extent of lichen cover, and the amount of soil and vegetative development found at the location of each deposit. Mapping of terminal positions allowed determination of advance and withdrawal rates, which, in turn, allowed inferences to be drawn regarding the climatic conditions controlling these rates.

## STUDY AREA

The focal point of this study is the outwash basin which lies directly south of the glacier's terminus (Figure 2). The current configuration of the basin was formed when a recent advance of the glacier incised the former valley floor. In doing so, the outwash basin now lies at an elevation far below that of the old valley floor -- about 40 meters. Till within the basin is much younger than the surrounding till of the former valley. The earlier valley till reflects longer exposure to weathering processes as exemplified by rounded rocks, extensive lichen cover, and greater degree of soil development. Conversely, rocks within the outwash basin are more angular and have little to no lichen cover. The sharp contrast existing between the former valley floor and the outwash basin suggests that the outwash basin was formed during the Little Ice Age (post 1650) and the upper "hanging" valley floor was formed perhaps as early as late Wisconsin time.

Figure 2. View south from West Gulkana Glacier Terminus. The post-1830 zone of retreat is below the dashed line.

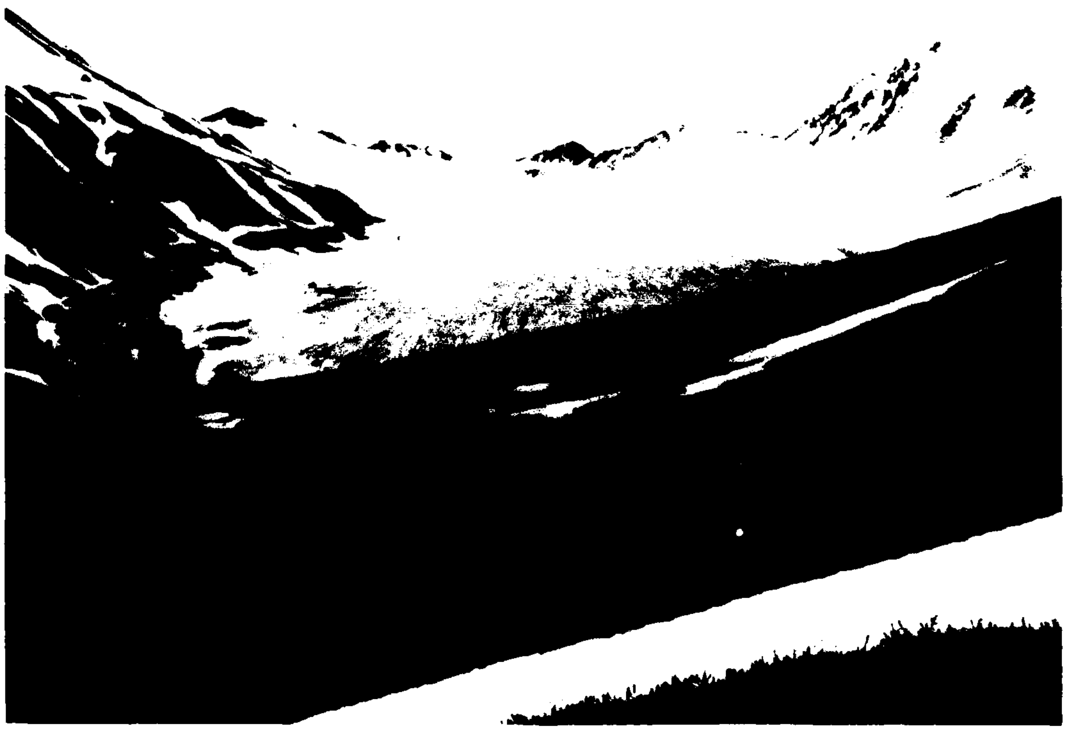

Figure 3. West Gulkana Glacier in 1910. Photograph by F.H. Moffit of U.S.G.S.

Figure 4. West Gulkana terminus in 1986. Note arrow marking 1910 terminal location.

## ADVANCE OF 1830

It is difficult to determine precisely when the last advance of the West Gulkana Glacier occurred. Reger (1968) attempted to reconstruct dates for recent advances and withdrawals of Gulkana area glaciers. Confronted with the problem of dating tills lacking organic material required for radiocarbon testing, he used lichenometric methods to reconstruct the recent history of the Gulkana and College Glaciers. Dating tills from known growth rate curves for specific lichen colonies (Beschel, 1950), he was able to successfully reconstruct the advances and withdrawals of the Gulkana and College Glaciers occurring during the Little Ice Age (c. 1500-1900).

Based on correlation with Reger's Gulkana and College Glacier chronologies, the West Gulkana's latest advance most likely occurred in 1830 -- the last year that both Gulkana and College Glaciers advanced. A lesser, subsequent advance of the Gulkana Glacier occurred in 1875, but College Glacier showed no such response. A likely explanation of why the Gulkana advanced and the College remained in equilibrium may be that the mean elevation of the Gulkana Glacier accumulation area is approximately 140 m higher than that of the College glacier.

Perhaps the depression of the region's climatic snowline, responsible for an increase in mass and subsequent terminal advance of the Gulkana in 1875, was not low enough to affect a similar terminus advance of the College Glacier. Because the accumulation area for the West Gulkana Glacier is approximately 60 m lower than the College Glacier accumulation area, it is probable that West Gulkana also did not experience an advance, but behaved as College Glacier. If an advance did not occur in 1875, it follows that the last date in which the present outwash basin was filled with ice was from the 1830 advance.

## 1830-1910

During this 80-year period, glacial thinning and retreat occurred slowly. A comparative inspection of Moffit's 1910 photograph (Figure 3) of the glacier and a 1986 photograph of the outwash basin provides an approximate terminus location for the glacier in 1910 (Figure 4). By 1910, the terminus had retreated northward approximately 125 m, for an average rate of 1.56 m/yr. This period of slow snout withdrawal coincides with the latter stages of the Little Ice Age (Sugden and John, 1982). The lack of lichen growth on outwash basin boulders indicates that significant glacial recession did not begin to occur until the end of the last century. Reger found no lichen on till which postdated the 1875 Gulkana moraines. Since the boulders in the outwash basin fit this description, this implies that the snout maintained its position at the point of maximum advance, or withdrew only slightly between 1830 and 1875 -- beginning a hastier recessional sequence thereafter.

## 1910-1957

This period in the glacier's history is characterized by thinning and retreat. Unlike the slow deterioration seen in the late 19th Century, the glacier rapidly thinned and the snout withdrew northward 375 m at an average rate of 7.98 m/yr. This rapid decay was in response to a warming trend which reached a peak during the 1940s (Figure 5; Dansgaard, 1971). Climatic warming during this period was shown to be a worldwide phenomenon by several researchers (Flint, 1971). Within the outwash basin, however, indications are that the glacier may have attained an equilibrium state prior to 1957. Approximately 35 m south of the 1957 terminus position is a distinct, if dissected, recessional moraine (Figure 6). This moraine arcs across the outwash basin on the east side of the axial stream, outlining a former terminus position and joining a less distinctive extension on the west side. The short-term equilibrium which produced this moraine probably occurred when hemispheric temperatures were declining after the 1940 maximum.

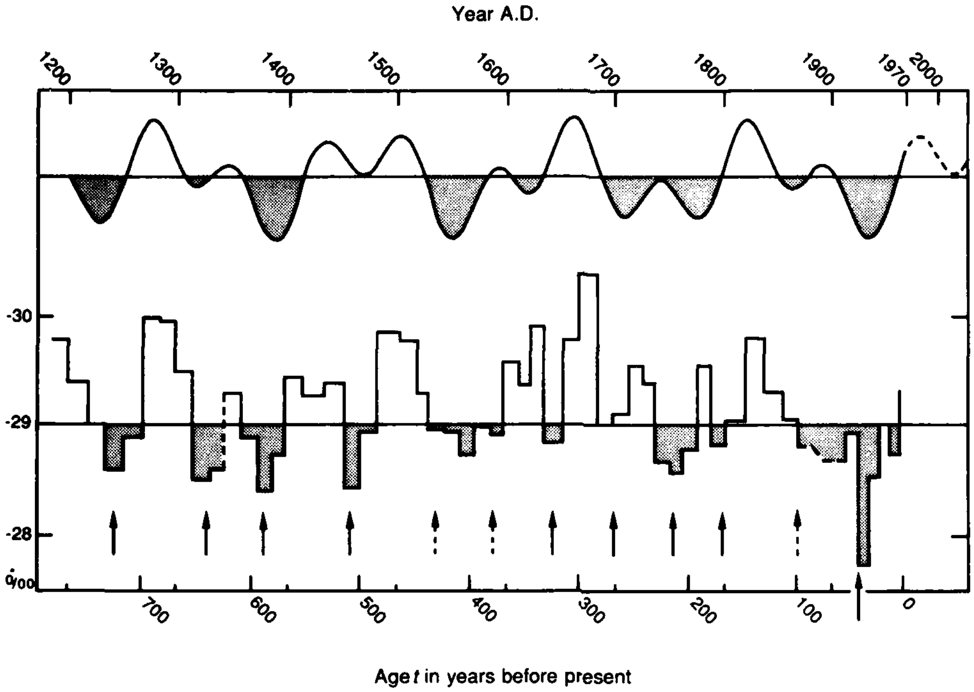


Figure 5. Curve developed from top part of Camp Century ice core, based on $O^{18}$ content (From Dansgaard, et al., 1971).

### *1957-1986*

A comparison of 1957 and 1986 photos reveals that rapid thinning and snout withdrawal continued until the present (Figures 6 and 7). The snout retreated 350 m at an average rate of 12.06 m/yr. Within this 350 m span, the floor of the outwash basin is relatively featureless. Several small recessional arcs occupy this portion of the basin, but it is largely covered by ground moraine (Figure 8). The lack of features in the outwash basin indicate that glacial decay was steady, never relaxing long enough to build substantial deposits. Comparison of the 1957 and 1986 photos reveals a drastic change in mass balance for the upper cirques which surround the valley. Cirque glaciers which were active along the upper rim of the valley in 1957 have atrophied into snowfields by 1986.

Interestingly, this period of rapid snout withdrawal and cirque glacier deterioration coincides with a recorded period of general climatic cooling. It is possible that there had been no

Figure 6. 1957 photograph of West Gulkana Glacier terminus. Note small recessional moraine in front of snout. (Photo from W.O. Field collection).

Figure 7. 1986 photo. Relative position of 1957 terminus can be identified on left.

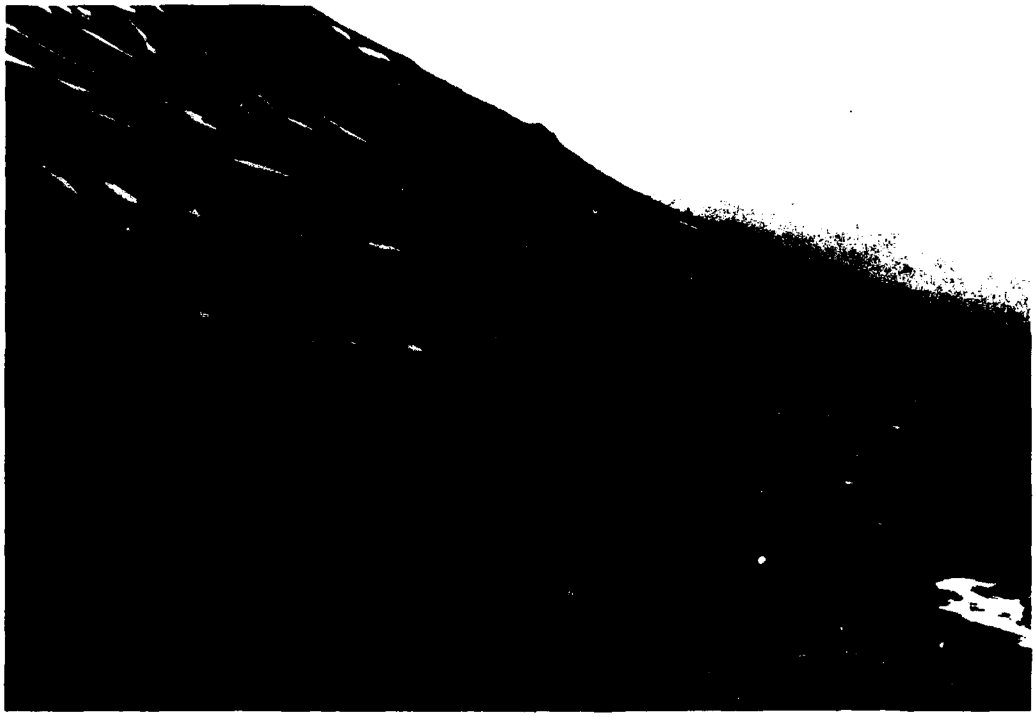

Figure 8. Proglacial zone directly in front of West Gulkana terminus, 1986.

advance because the glacier's response to cooler temperatures experienced a lag. Mayo and Trabant (1986) suggest that the Gulkana and other valley glaciers in the region have been thickening in their accumulation areas since 1976 in response to a change in climatic conditions. Initial field observations of the glacier's small accumulation area and surrounding cirque basins in the summers of 1986 and 1987 suggested this had not happened on West Gulkana Glacier, however, a small wave does appear in comparison of the 1957 and 1986 topographic maps (Chambers, this volume). Differences in magnitude of thickening between the two glaciers can be attributed to the lower mean elevation (200 m) of the West Gulkana accumulation area.

## CONCLUSIONS

Glaciers in other regions of Alaska have behaved in a manner similar to West Gulkana. In the Wrangell Mountains, for example, most glaciers experienced their last advances near the turn of the century and have been receding ever since (Field, 1975). Field notes that even in the Coast Ranges, where winter precipitation far exceeds that received in the Alaska Range, large numbers of advancing glaciers last occurred in the late 1800s -- followed by a long recessional sequence to the present. Studies on the McCall Glacier (Dorrer and Wendler, 1976) in the drier Brooks Range of Northern Alaska also indicate that rapid deterioration of glacier mass has been the norm in the latter half of this century. The common glacier behavior found in each of these regions has been Twentieth Century retreat, following a Nineteenth Century advance.

The West Gulkana Glacier's last measurable advance was c. 1830. The snout receded slightly until 1910 as climatic warming followed the Little Ice Age. At the turn of the century, the pace of glacial decay accelerated as the terminus retreated rapidly. Withdrawal continued through the 1940s until equilibrium was reached, although briefly. Since the 1950s, the glacier has been thinning and retreating at its fastest rate.

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# SUMMER 1986 RADIATION BALANCE, WEST GULKANA GLACIER, ALASKA: THE EFFECTS OF CHANGING SURFACE CONDITIONS

by

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## INTRODUCTION

Glacier ablation is dictated by the resultant of several energy flows into and out of a glacier mass. These energy budget variables are controlled both by weather and earth surface conditions. As part of the larger energy budget, components of the surface radiation balance have been identified as important in determining energy available for ablation processes. In many environments, surface conditions are relatively constant. In glacier environments, however, the surface can rapidly change and substantially affect the radiation balance. This study examines the effects of both weather and changing surface conditions on summer radiation balance components over the West Gulkana Glacier, Alaska.

## SITE LOCATION

The West Gulkana Glacier is located at 63$^{o}$ 16'N, 145$^{o}$ 28' W on the south side of the Central Alaska Range, Alaska. This well-entrenched valley glacier is approximately 4 km long, 1 to 1.5 km wide, and covers an elevation range from 1300 to 2400 m. The West Gulkana Glacier flows south-southeast and numerous other glaciers are located nearby (Frontispiece and Figure 1 in Marcus and Reynolds, this volume).

A meteorological instrument site was established in the ablation zone of the glacier about 100 meters upglacier from the 1986 base camp at an elevation of 1520 meters. During the summer season, the glacier surface at the instrument site changed dramatically from snow to slush to ice as ablation proceeded

(Figures 1, 2, 3). The snow surface (representing the previous winter's accumulation) was generally smooth with high albedo. The slush surface had a very high density (c. 0.78 g $cm^{-3}$) and took on a grayish color tone. Finally, bare glacier ice was quite rough and irregular, covered with fine rock debris, and dark in appearance. Although base camp had to be moved to a nearby lateral moraine half-way through the season, the meteorological site was sustained at its original location.

## COLLECTION AND REDUCTION OF DATA

Standard surface meteorological observations were taken from 21 June to 19 July 1986. Observations were made every three hours daily from 0700 to 1900 Alaska Daylight Time. Continuous hourly observations were made during three intensive observation periods (27-29 June, 5-7 July, and 17-19 July). Data collected included: cloud cover, type and direction of movement; wet and dry-bulb temperatures; wind speed and direction; surface conditions; visibility up and down valley; and precipitation amounts. A five-stake ablation farm was also maintained.

Radiation measurements began on 27 June and continued through 19 July. Observations were recorded at 15-minute intervals throughout the period. Data collected included: fluxes of shortwave and net radiation; surface and subsurface temperature; and measurements of screen-level temperature and humidity. Wet and dry-bulb temperatures were measured with a ventilated psychron. Incoming shortwave radiation was monitored by an Eppley PSP pyranometer sensitive to radiation from 0.285 to 2.8 microns. Outgoing or reflected shortwave radiation was measured by a Yellott photovoltaic solarimeter, sensitive from 0.35 to 1.15 microns. Net radiation was monitored by a Micromet net radiometer which measures both longwave and shortwave radiation from 0.3 to 6.0 microns. The general form of the radiation balance is expressed as:

$$Q^{*} = K - K + L - L$$

where $Q^{*}$ is net all-wave radiation, K and K represent incoming and reflected solar radiation, and L and L are fluxes of

Figure 1. Snow surface at main glacier site in mid-June.

Figure 2. Slush conditions, West Gulkana Glacier.

Figure 3. Bare glacier ice, late July, 1986.

incoming and outgoing longwave (infrared) radiation. Since fluxes of longwave radiation were not specifically measured, they had to be estimated. The glacier was found to be isothermal at $0^{\circ}C$; thus fluxes of outgoing longwave radiation remained constant at 315.868 W $m^{-2}$. Longwave incoming radiation was calculated as the residual of the radiation balance equation.

To smooth the data and provide for more meaningful comparisons, radiation data were reduced to hourly and daily totals. Instantaneous values recorded were assumed to be representative of the fifteen-minute period between observations, and, therefore, were totaled for that period. These fifteen-minute totals were then summed to obtain hourly values. The daily totals were obtained as the sum of the hourly values. Hourly and daily albedo values were calculated as the mean of all observations.

In micrometeorological studies (particularly those in harsh environments), sources of potential error are numerous. According to manufacturer's specifications, the Eppley PSP has a potential error of 1.0%, and the Yellott solarimeter of 5.0%. The manufacturer's information did not list an error value for the net radiometer, but it is estimated to be 5.0%. The differences between the spectral sensitivities of the various instruments introduces an element of error in the results as well.

In glacier studies, weather conditions can often affect instrument precision. Accumulation of snow, rime, or condensation on the dome of the instruments, will attenuate the amount of light reaching them. In particular, the net radiometer was prone to condensation during rainy periods toward the end of the season. The rapid ablation (c. 4 cm per day) of the glacier surface made it virtually impossible to keep the instruments level at all times. Instrument stands were checked and re-leveled periodically, but some resultant error was surely introduced.

The last potential source for error lies in reduction of the data. Values for fluxes of longwave incoming radiation were calculated as a residual from other measured fluxes. Errors in the longwave incoming term could potentially amount to the sum of all errors which went into its calculation. This suggests that the calculated longwave radiation could be 11% due to normal instrument error alone.

## WEATHER CONDITIONS

The 1986 micromet field season on the West Gulkana Glacier was characterized by rapidly changeable weather, sudden high precipitation amounts and, above all, extreme wind gusts (see Brazel and Moore, this volume). In all, there were three discernable weather periods. The first, from 20 June through 25 June was a period of late winter weather, cold temperatures, and precipitation. The second from 26 June through 6 July held clear skies, warm temperatures, and spotty precipitation. The final period, 7-19 July saw colder temperatures, frequent precipitation, and generally overcast skies including occasional fog.

Cloud cover varied greatly between the three periods (Figure 4). The most cloud-free period was from 26 June through 6 July. With the exception of frontal activity in the latter stages of the season, cloudiness generally came in the form of afternoon cumulus activity. On average, there were few clouds early, building to a maximum in the late afternoon. These afternoon clouds often developed into large cumulonimbus with accompanying rain and lightning.

## SUMMER SEASON RADIATION BALANCE

As stated, the radiation balance was measured over snow (27 June - 10 July), slush (10 - 13 July) and ice (13 - 19 July) (Tables 1, 2). These surface changes had recognizable effects on the surface radiation balance.

The most important change influenced by surface conditions was on surface albedo (Figure 4). The snow surface held a fairly constant albedo around 74% until 7 July, when melting accelerated. As melting continued, the albedo dramatically dropped reaching 29% just prior to the surface changing to slush on 10 July. Over the whole period, the snow albedo averaged 68%.

Once the surface changed, the albedo rapidly increased back to 51%. This was caused by freezing of the slush layer on 11 July. On this date, the surface became visibly "whiter" in appearance. As slush began to melt, the albedo dropped again. By the morning of 13 July, the slush had completely melted; only glacier ice remained, with an albedo of 28%. The mean albedo for slush was 41%.

During the remaining observation period, as the ice surface became rougher and dirtier from differential melting, the albedo slowly declined from 28% to a low of 15% (19 July). Mean ice albedo was 22%. Low albedo values of this glacier ice are due to the health of the glacier as a whole. The West Gulkana Glacier is in a recessional phase and its ice is quite stagnate, supporting considerable fine to medium sediments on its upper

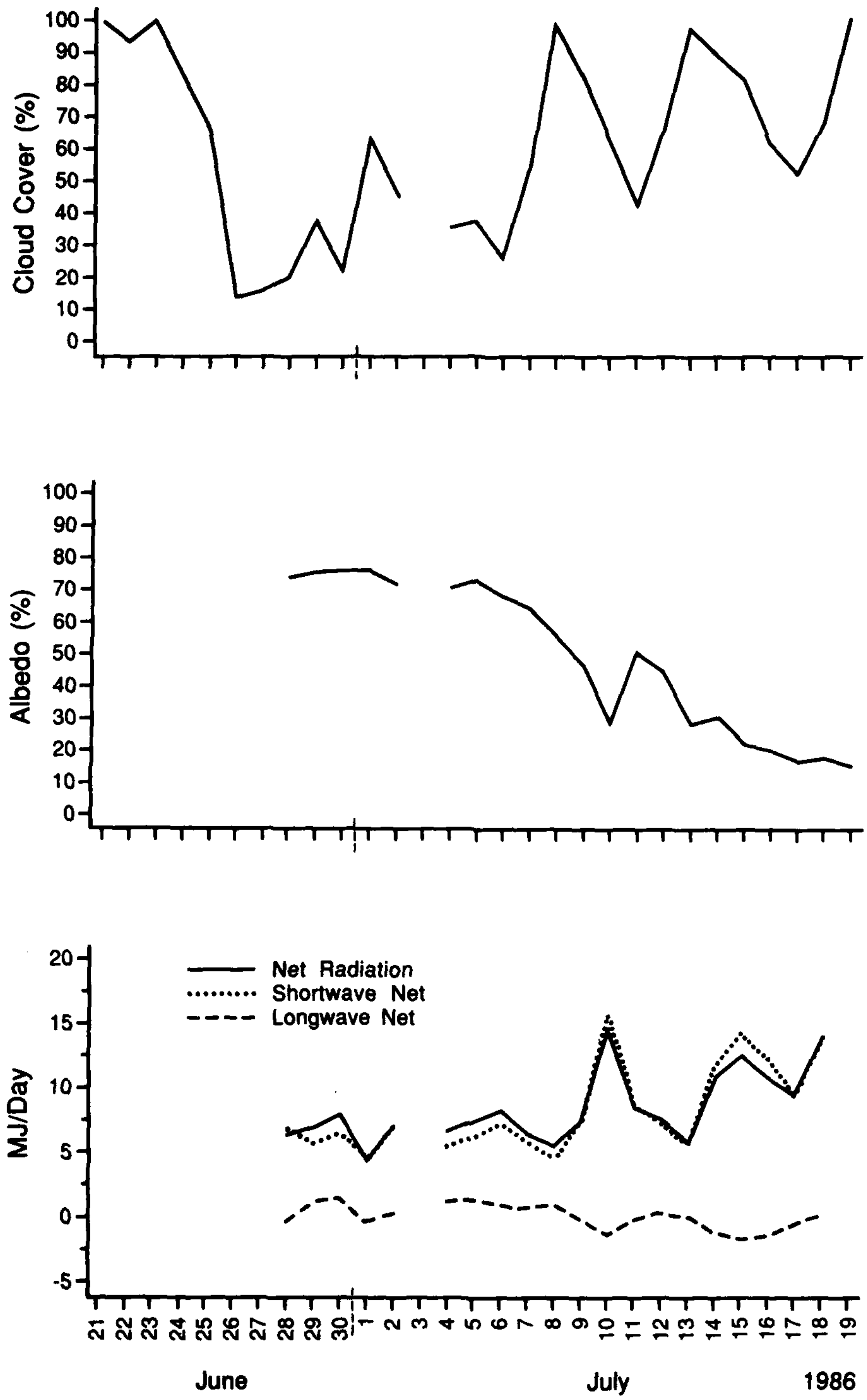


Figure 4. Cloud cover, albedo, and radiation components: 1986 field season, West Gulkana Glacier.

## TABLE 1

**MEAN DAILY RADIATION TOTALS: 28 JUNE - 18 JULY**

| Date | K↓ | K↑ | Albedo | L↓ | $Q^*$ |
|---|---|---|---|---|---|
| 28 | 25.85 | 19.04 | 74% | 26.83 | 6.35 |
| 29 | 23.61 | 17.85 | 76% | 28.44 | 6.91 |
| 30 | 27.01 | 20.55 | 76% | 28.77 | 7.94 |
| 1 | 19.27 | 14.66 | 76% | 26.97 | 4.29 |
| 2 | 24.11 | 17.34 | 72% | 27.57 | 7.05 |
| 3 | | | missing data | | |
| 4 | 18.51 | 13.08 | 71% | 28.55 | 6.69 |
| 5 | 22.90 | 16.70 | 73% | 28.69 | 7.60 |
| 6 | 22.75 | 15.45 | 68% | 28.21 | 8.22 |
| 7 | 16.15 | 10.36 | 64% | 28.04 | 6.53 |
| 8 | 10.31 | 5.73 | 56% | 28.27 | 5.57 |
| 9 | 14.30 | 6.71 | 47% | 27.16 | 7.46 |
| 10 | 22.36 | 6.39 | 29% | 25.94 | 14.63 |
| 11 | 17.91 | 9.07 | 51% | 27.02 | 8.57 |
| 12 | 13.01 | 5.78 | 44% | 27.71 | 7.65 |
| 13 | 8.06 | 2.30 | 28% | 27.39 | 5.86 |
| 14 | 17.31 | 5.34 | 31% | 26.18 | 10.86 |
| 15 | 18.50 | 4.11 | 22% | 25.63 | 12.73 |
| 16 | 15.37 | 3.09 | 20% | 25.96 | 10.96 |
| 17 | 11.71 | 1.95 | 17% | 23.58 | 9.46 |
| 18 | 16.75 | 2.96 | 18% | 27.58 | 14.09 |

All radiation values in MJ/day. K↓ and K↑ are fluxes of incoming and outgoing shortwave radiation; L↓ is incoming longwave radiation; and $Q^*$ is net radiation.

TABLE 2
MEAN HOURLY RADIATION TOTAL: 28 JUNE - 18 JULY

| Time | K↓ | K↑ | Albedo | L↓ | Q* |
|---|---|---|---|---|---|
| 0100 | 0.25 | 0.10 | 83% | 1103.97 | -33.00 |
| 0200 | 0.00 | 0.00 | | 1093.85 | -43.27 |
| 0300 | 0.07 | 0.00 | | 1094.80 | -42.26 |
| 0400 | 4.15 | 2.74 | 89% | 1098.05 | -37.66 |
| 0500 | 30.37 | 17.31 | 50% | 1091.24 | -32.83 |
| 0600 | 94.13 | 47.46 | 49% | 1081.54 | -8.92 |
| 0700 | 161.97 | 75.01 | 50% | 1072.66 | 26.45 |
| 0800 | 441.55 | 262.62 | 54% | 1133.13 | 183.89 |
| 0900 | 911.64 | 578.96 | 57% | 1230.41 | 442.59 |
| 1000 | 1146.88 | 681.13 | 54% | 1253.70 | 603.51 |
| 1100 | 1442.12 | 874.80 | 55% | 1258.59 | 715.81 |
| 1200 | 1644.28 | 938.79 | 52% | 1258.07 | 858.51 |
| 1300 | 1838.69 | 1042.38 | 52% | 1227.80 | 924.90 |
| 1400 | 1871.37 | 1029.06 | 51% | 1210.52 | 955.82 |
| 1500 | 1930.15 | 1069.59 | 51% | 1190.07 | 913.51 |
| 1600 | 1885.17 | 1016.21 | 50% | 1151.50 | 883.34 |
| 1700 | 1508.22 | 817.64 | 50% | 1155.85 | 709.32 |
| 1800 | 1242.04 | 664.14 | 50% | 1128.75 | 569.52 |
| 1900 | 904.88 | 460.00 | 50% | 1097.40 | 405.15 |
| 2000 | 638.89 | 340.15 | 50% | 1094.31 | 255.94 |
| 2100 | 350.30 | 171.99 | 49% | 1094.49 | 135.67 |
| 2200 | 132.02 | 64.54 | 49% | 1110.01 | 40.38 |
| 2300 | 41.47 | 21.15 | 48% | 1112.08 | -4.72 |
| 2400 | 8.99 | 4.92 | 67% | 1102.66 | -30.40 |

All radiation values in KJ/hr. See Table 1 for nomenclature.

layers. Streten and Wendler (1968) similarly found an average albedo of 19% over the Worthington Glacier, where the ice also contained small bits of debris.

Table 3 presents typical albedo values found over glacier surfaces. The values for the snow on the West Gulkana agree most closely with those reported by Geiger (1965); and of Wendler and Streten (1969) who were working on the Lemon Creek Glacier in Southeastern Alaska. The values for ice are generally lower than others have reported, but are fairly close to those of Geiger (1965) (dirty ice), and Aufdemberge (1971) (Capps Glacier). The literature lacks a comparative figure for slush albedo, but, as might be expected, it falls between that of snow and that of ice. Generally, it comes close to the range of 20% to 50% which Geiger (1965) states for dirty firn.

The changes in surface albedo during the season had a marked effect on the radiation balance components. Figure 4 shows the trends in the fluxes of net shortwave, net longwave, and net radiation during the summer, 1986. As might be expected given the albedo trends, the net shortwave radiation receipt gradually increased through 10 July, declined during the slush phase, and then continued its rise after 13 July.

Net longwave radiation remained fairly constant throughout the summer season, declining slightly as the season progressed. Net radiation was largely dictated by the changes in shortwave radiation. The seasonal pattern of net radiation followed the fluctuations in net shortwave almost exactly; thus, changes in surface albedo significantly affected the net input of energy to the glacier.

Few researchers have found this dominance of shortwave radiation, especially under cloudy conditions. Most studies (Sauberer and Dirmhirn 1952; Hoinkes 1970; Holmgren 1971; Ambach 1974) have shown that under cloudy conditions, the longwave incoming radiation component becomes quite large, since the clouds generally have a warmer temperature than the clear sky. This leads to a positive longwave net radiation, and the longwave flux becomes dominant in determining net radiation.

TABLE 3

TYPICAL ALBEDO VALUES

| Author | Albedo | Surface |
|---|---|---|
| Aufdemberge (1971) | 20 - 45% | Ice |
| Eaton & Wendler (1982) | 30 - 60% | Snow |
| Geiger (1965) | 70 - 95% | Fresh Snow |
| | 40 - 70% | Old Snow |
| | 50 - 65% | Clean Firn |
| | 30 - 46% | Clean Ice |
| | 20 - 50% | Dirty Firn |
| | 20 - 30% | Dirty Ice |
| Keeler (1964) | 37 - 60% | Snow |
| Paterson (1969) | 70 - 90% | Fresh Snow |
| | 40 - 60% | Firn |
| | 20 - 40% | Ice |
| Streten & Wendler (1968) | 19% | Ice |
| Wendler & Streten (1969) | 65% | Snow |
| Wendler & Weller (1974) | 58 - 80% | Snow |
| | 48% | Ice |
| This Study | 47 - 76% | Snow |
| | 29 - 51% | Slush |
| | 15 - 31% | Ice |

On the West Gulkana, cloudiness seemed to have little effect on the net longwave radiation and the shortwave flux dominated. This anomaly may be related to varying amounts of valley-wall emittance, but this has not yet been investigated. Streten and Wendler (1968) also observed dominance of the shortwave fluxes under cloudy skies on the Worthington Glacier, but offered no reason for their finding.

To gain a more detailed view of radiation balance changes with varying surface conditions, three separate days (30 June, 11 July, and 18 July), each representative of the different surface

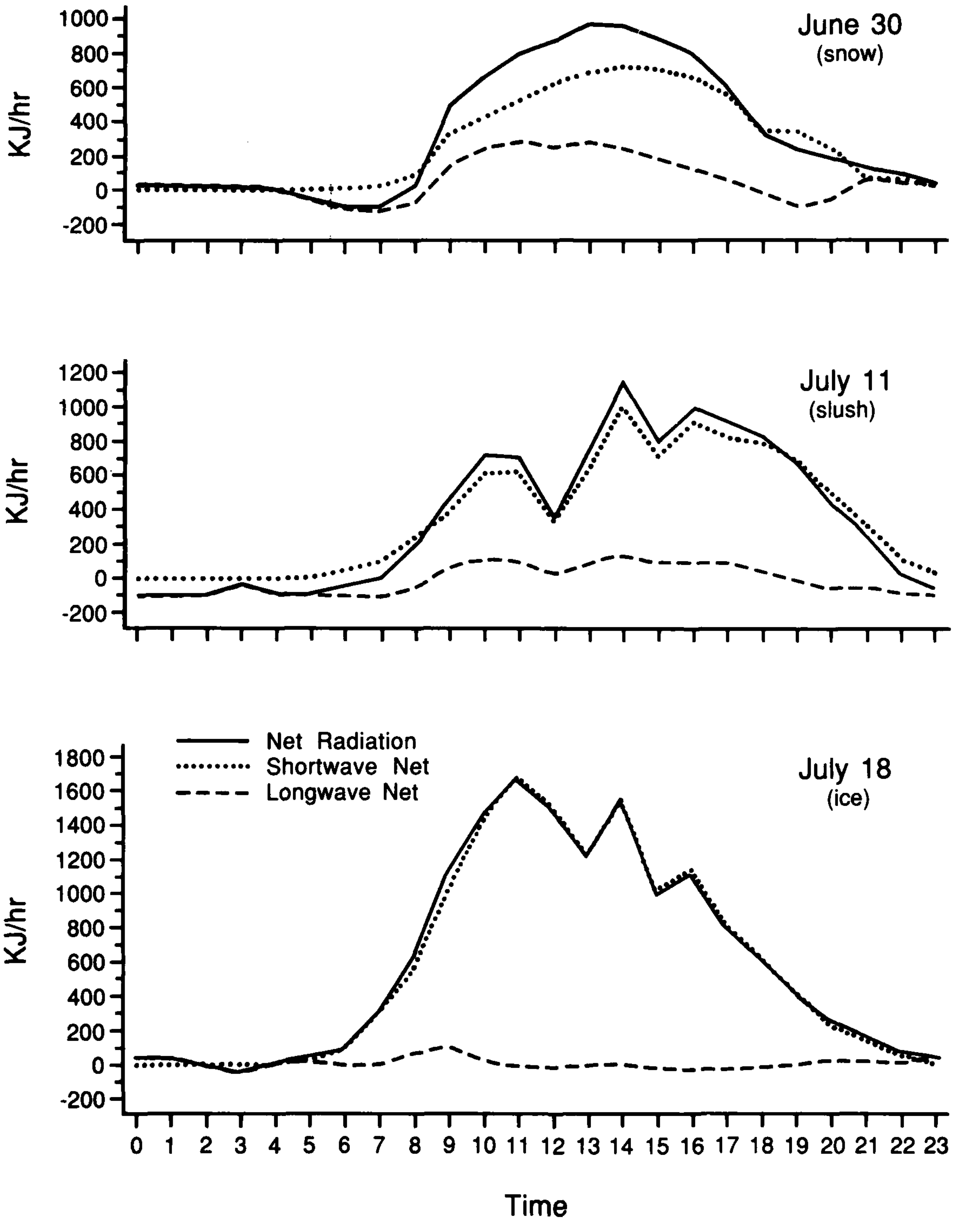


Figure 5. Individual radiation components over snow, slush, and ice surfaces.

conditions (snow, slush, and ice), were chosen for closer scrutiny (Figure 5). These days were selected because they had as little cloud cover as possible.

The diurnal curves of net shortwave, net longwave, and net radiation all show similar patterns to that of the mean pattern discussed earlier. Net radiation in all cases is tied closely to the net shortwave radiation. Net longwave radiation is slightly greater over the snow surface. This is not a result of changing surface conditions, however. For the entire summer, the surface was found to be isothermal at $0^{\circ}C$, and longwave outgoing radiation was, therefore, constant. It follows that net longwave radiation primarily results from changes in atmospheric emittance.

## SUMMARY

Summer 1986 trends in radiation balance components were analyzed to determine the effect of changing surface conditions. Measurements were made as the surface changed from snow to slush to ice. Surface albedo was affected most by changes in surface conditions. Over snow, the mean albedo was 68%. This dropped to 41% for slush and 22% for ice. The relatively low value for glacier ice is attributable to sediments in and on the upper layers of the glacier. All albedo values are consistent with other studies.

Changing surface conditions also affected the other radiation balance components. On both a seasonal and a diurnal time scale, net longwave radiation remained relatively constant near zero despite large amounts of cloud cover. This caused net radiation to be dominated by the net shortwave component. Since net shortwave radiation is largely controlled by surface albedo, changing albedo appears to be the most important boundary layer condition determining net radiation.

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**VALLEY WALL LONGWAVE FLUX CONTRIBUTIONS, WEST GULKANA GLACIER, ALASKA**

by

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## INTRODUCTION

Long-wave radiation and valley wall temperatures were observed on the West Gulkana Glacier as part of the larger climate research program during the summer, 1986 field season. The main observation point was at 1495 m in the center of the glacier at the main meteorological station (Figure 1). Specifically, the question of what portion of the total incoming longwave radiation was being contributed by the surrounding valley walls of the glacier is explored in this paper.

In order to understand the contribution of incoming longwave radiation and how it relates to the glacier heat balance, a brief description of the glacier's surface energy budget is necessary. Based on the principle of conservation of energy, the surface energy budget includes six major components related by

$$R_n = G + LE + H + M + P \qquad (1)$$

where $R_n$ = net radiation,
$G$ = subsurface heat flux,
$LE$ = latent heat flux,
$H$ = sensible heat flux,
$M$ = melt heat equivalent,
and $P$ = heat of melt from rainfall.

For an accurate assessment of the surface energy exchange at the glacier surface, each aspect of this energy balance must be evaluated (Marks and Dozier, 1979).

The radiation component of the energy budget, Rn, is an important source of heat energy to the glacier surface. The radiation inputs are related by the radiation balance equation:

$$R_n = S\downarrow + L\downarrow - S\uparrow - L\uparrow \tag{2}$$

or

$$R_n = (1 - \alpha)S\downarrow + L\downarrow - \varepsilon\sigma T_s^4, \tag{3}$$

where $R_n$ = net radiation,

$S\downarrow$ = incoming shortwave radiation,

$L\downarrow$ = incoming longwave radiation,

$S\uparrow$ = reflected shortwave radiation,

$L\uparrow$ = emitted longwave radiation from snow/ice,

$\varepsilon$ = surface emissivity (1.0),

$\sigma$ = Stefan-Boltzmann constant,

$\alpha$ = albedo

and $T_s$ = snow, ice interface temperature.

This paper focuses on the incoming longwave element, $L\downarrow$. The longwave radiation received by the glacier is particularly important because the net shortwave radiation is usually small on snow/ice surfaces due to the high surface reflectivity. Additionally, shortwave radiation is received only during daylight hours when the sun is above the horizon. Longwave radiation, however, is incident at all hours of the day. The major sources of incoming longwave radiation are the atmosphere (air, aerosols, and clouds) and surrounding terrain. The surrounding terrain is rarely studied as a radiation balance component in glacier studies. In alpine areas of high relief such as the West Gulkana Glacier, however, terrestrial radiation may account for significant $L\downarrow$ receipt on the glacier. Bounded to the east and west by relatively steep, imposing valley walls, the West Gulkana Glacier may be receiving significant levels of longwave radiation from these slopes (Marcus, et al., 1981 and Brazel and Marcus, 1987) because of the apparent greater degree of ablation observed at the glacier margins compared to mid-glacier. It is hypothesized that this difference in ablation

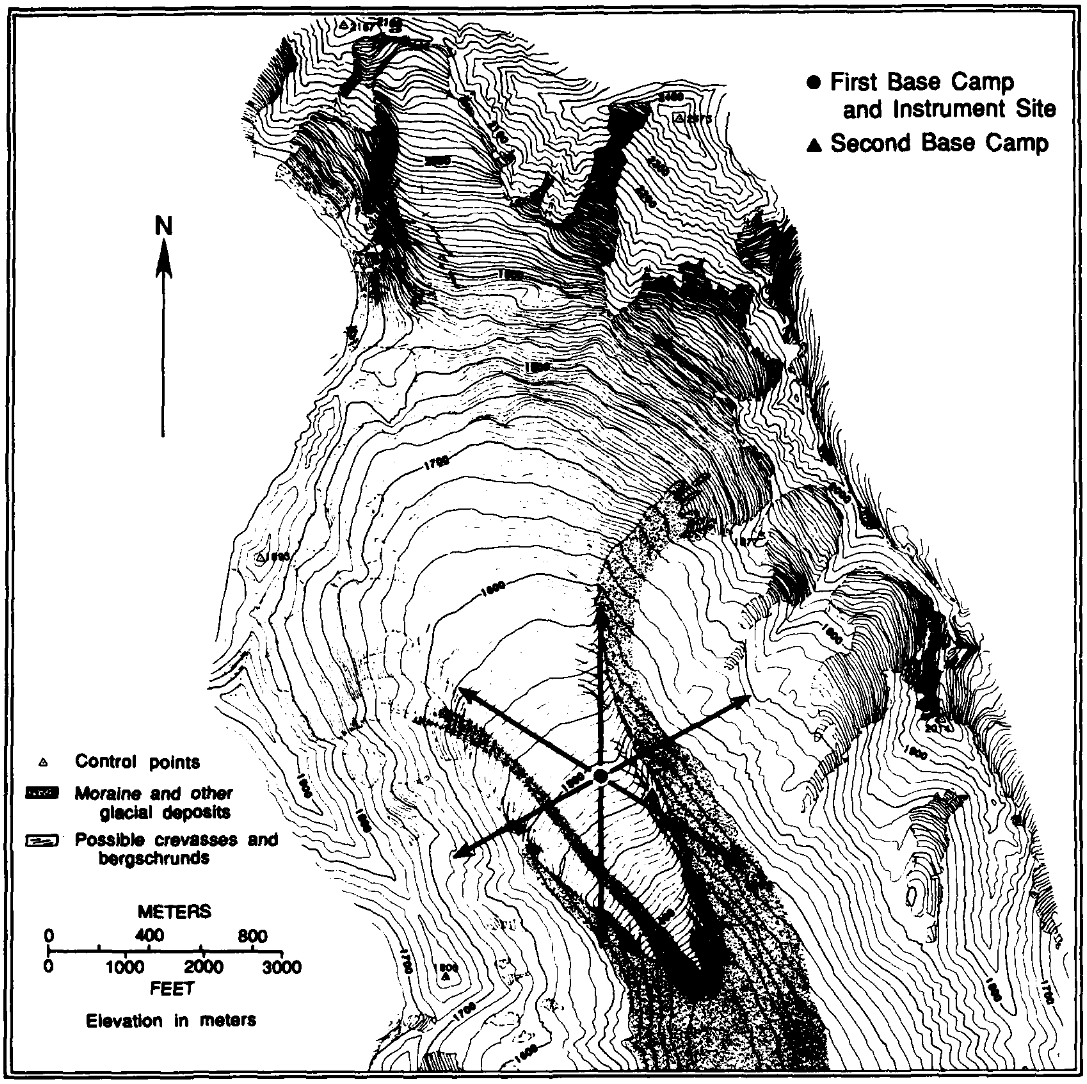


Figure 1. West Gulkana Glacier, 1986. Arrows represent infrared lines of sight.

magnitude may be due to the obstruction of the overhead sky dome at the glacier margins which consequently increases the contribution of L↓ from the valley wall side slopes. Although ablation is not directly studied in this paper, the L↓ question is addressed in this study.

## METHODOLOGY

In order to calculate valley wall input to L↓ , the total incoming longwave radiation from both the atmosphere and surrounding terrain must first be measured and/or estimated. Several methods are available to estimate $L\downarrow$. One utilizes the radiation balance equation, applying measured budget terms to the rearranged equation (Eq. 2):

$$L\downarrow = R_n - S\downarrow + S\uparrow + L\uparrow \qquad (4)$$

On the glacier, net radiation, $R_n$, was measured using a net radiometer. The incoming short wave, $S\downarrow$, and reflected short wave, $S\downarrow$, were measured by solar radiometers. All observations were taken approximately on the longitudinal axis of the glacier (Figure 1) and spanned the period July 4-17. For the glacier surface, $L\uparrow$ is calculated by using the Stefan-Boltzman law. Surface temperatures were consistently near 0 $^{o}$C during the observation period. Thus, $L\uparrow$ is assumed fixed at a constant flux for that temperature. Further, glacier surface emissivity is assumed equal to 1.0.

The remaining element, $L\downarrow$, can now be calculated by substituting in the known values of $R_n$, $S\downarrow$, $S\uparrow$, and $L\uparrow$ into equation 4. Once $L\downarrow$ is determined, the contribution of the surrounding valley walls is computed and compared to $L\downarrow$ to ascertain valley wall contributions.

The first step in evaluating valley longwave wall contributions entails using slope temperatures and emissivities and the Stefan-Boltzman equation. However, the problem is complicated by varying amounts of snow cover on the rock-strewn inclines during the summer season. Because the emissivity and temperature of the snow is quite different from that of rock surfaces, a procedure had to be developed to sample surrounding slopes and determine an average value for longwave flux emitted by the surrounding walls.

To utilize the Stefan-Boltzman equation, the temperatures and emissivities of the two surface types must be isolated. To sample the slope temperatures, a remote sensing device was necessary as measurements with thermometers in contact with the slopes themselves would have required many thermometers and extensive manpower, to make observations. Moreover, direct measurements would probably not provide accurate, aggregate samples of slope temperatures. The best approach available was to select an observation point at mid-glacier and remotely sense the surface temperatures with a Barnes IR thermometer.

This instrument measures the longwave radiation emitted by surfaces within its 2.8$^{\circ}$ field-of-view. Radiation sensed by the instrument is limited to the 8-14μm waveband; maximum levels of longwave radiation from the terrain occur in the 8-15μm waveband. Thus, the Barnes IR thermometer closely measures the required wavelength range. Moreover, although the instrument senses both emitted and reflected longwave radiation, the reflected term can be ignored because most natural surfaces are near perfect absorbers of radiation in these given wavebands (Oke, 1981). Lastly, an assumption was made that little absorption of the longwave radiation from the slopes occurs in the intervening space between the slopes and the point of observation. Because of the above reasons, this apparent radiative temperature can be equated to the slope surface temperature.

The sighting vectors for sampling the surrounding terrain were selected on the following basis. Because the ridges to the north are a great distance upglacier from the observation point, they are less significant as sources of emission to glacier locations (Figure 1). In addition, given the field of view and large distance to the slopes, there is a possibility of inadvertently sampling sky temperatures. To the south, all slopes fall away to the glacier terminus. In contrast, high and steep walls, paralleling the longitudinal axis of the glacier, rise to the east and west and in proximity to the mid-glacier observation point. As a result, the east and west inclines alone were sampled.

Three target sensing points were selected at approximately mid-slope on both side walls (see target azimuths as dashed lines in Figure 1). Prominent terrain features were chosen as targets to achieve consistency in measurement locations. Measurements of the slope temperatures for each target area were made every three hours from 0700h to 1900h daily (4 - 17 July, 1986); a few night observations were made hourly from 2000h to 0600h to analyze diurnal trends more closely. In addition to the IR temperature measurements, a number of other meteorological parameters were simultaneously measured at the main weather station site: temperature, relative humidity, cloud cover, wind speed, visibility, and short and longwave radiation components.

The infrared temperatures for the target areas represent an integration of the longwave radiation emitted from the area. Consequently, the temperature cannot be substituted directly into the Stefan Boltzman equation because emissivity and temperature variations between snow and rock surfaces must be proportionally determined. Hence, the aggregate temperature must be separated into its component temperatures so that calculations can be made for the two surfaces individually.

Assuming a snow temperature of $273^{\circ}K$, the temperatures of the rock remains to be determined. The following relationship was developed to calculate the apparent temperature:

$$T_{sl} = fs\ (T_s) + fr\ (T_r) \qquad (5)$$

where $T_{sl}$ = aggregate temperature of the slope target area recorded by the Barnes thermometer,

$fs$ = fraction of slope target area covered by snow,

$T_s$ = temperature of snow,

$fr$ = fraction of slope target area not snow-covered (i.e., rock)

and $T_r$ = temperature of the rock surface.

In order to determine snow cover, panoramic photographs were taken periodically of the side slopes to show the progression of snowmelt on the slopes through the period of observation. Because these photographs were taken only at the beginning, middle, and end of the season, the snow cover in the intervening periods had to be approximated. This was done by assuming a linear melt pattern. As each target point on the side slopes represented a unique target area in size and shape, the area being viewed by the thermometer had to be determined to utilize these photographs.

Knowing the instrument's field of view ($2.8^{\circ}$), the distance to the target point, the height of the target point above the observation point, and the slope of the side walls, the dimension of the area sensed can be approximated. For all target areas, the shape was assumed to be elliptical although some distortion occurs in target areas which are not normal to the observation point. After plotting these areas on a topographic map, they were compared to the photographs to estimate the fraction of area covered with snow. Finally, the apparent rock temperatures were calculated using Equation 5.

Once apparent rock temperatures are known, the Stefan Boltzman law is employed to compute the longwave radiation emitted from each target area. The expression for target area longwave flux, separated into terms for each surface, becomes:

$$L_{STA} = \varepsilon_s \sigma T_s^4 fs + \varepsilon_r \sigma T_r^4 fr \quad (6)$$

where $L_{STA}$ = longwave flux emitted from the slope target area,

$s$ = emissivity of snow,

$\sigma$ = Stefan Boltzman constant,

$T_s$ = Kelvin temperature of snow,

fs = fraction of the slope target area covered with snow,

$\varepsilon_r$ = emissivity of the rock surface,

$T_r$ = Kelvin temperature of the rock surface,

fr = fraction of slope target area not snow-covered (rock).

The rock emissivity was estimated based on tables giving emissivity values for various rock types (Colwell, 1983). On the west facing slopes, the rock samples taken consisted of combinations of andesite, diorite, and peudatite, corresponding to an emissivity of approximately 0.91. On the east facing slopes, a similar mixture was observed except for a higher concentration of andesite, raising the emissivity to approximately 0.92. During periods of rains, moisture on the rocks increased the emissivity as water has an emissivity between 0.92 and 0.96 (Sellers, 1965); the values of the west and east facing slopes became 0.94 and 0.95 respectively.

After calculating $L_{STA}$ for each of three target areas on west and east slopes, an average value of the total longwave terrestrial flux from both west and east walls was calculated using the relationship:

$$\left[ \sum_{i=1}^{3} L_{ESTA_i} /3 + \sum_{j=1}^{3} L_{WSTA_j} /3 \right] = L_{SL} \quad (7)$$

where $L_{ESTA}$ = longwave flux from east facing wall target area i,

$L_{WSTA_j}$ = longwave flux from what facing wall target area j,

and $L_{SL}$ = total longwave flux from surrounding walls.

The three values from each wall were first averaged because they are per unit area with dimensions of energy per unit time per unit area ($cal/cm^2 min^{-1}$), and an average value of the flux is needed to integrate the varying fluxes of each wall. These averaged flux values are then added to approximate the total flux representative of all the east/west sloping terrain of importance.

$L_{SL}$ is not, however, representative of the true total longwave flux received at the observation point at mid-glacier. In addition, the contribution of the terrain is only a part of the total incoming radiation, $L\downarrow$, as the overlying atmosphere also contributes $L\downarrow$ to the glacier. $L_{SL}$ must be made representative of only those slopes that are significant contributors of longwave flux. The degree of relief of the slope was the criteria employed to evaluate significance. All slopes in the $360^o$ radius around the observation point were evaluated.

A sky horizon chart (Figure 2) was constructed based on a central point at the observer station. Those sectors having vertical angles greater than or equal to $10^o$ were arbitrarily designated as significant slope radiators due to their high relief. Once these sectors were distinguished, the fraction of the sectors that were considered significant was multiplied by $L_{SL}$. Approximately 70% of the slope sectors satisfied the $10^o$ criteria and $L_{SL}$ was appropriately scaled.

Because the surrounding terrain obscures only a small

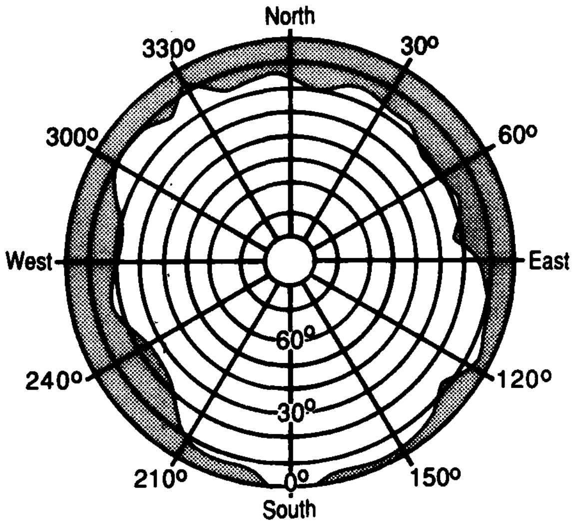


Figure 2. Sky Horizon Chart for the main camp observation site.

portion of the total sky hemisphere, $L_{SL}$ has to be further adjusted. This is accomplished by employing the sky view factor (SVF). The sky view factor is the ratio of the sky hemisphere which is "seen" from a given point on the surface to that which is potentially available (Oke, 1981). This ratio is expressed as a number between 0 and 1. In other words, the view factor represents the portion of the $180^{o}$ sky dome which is unobscured by the surrounding terrain. Sky view factor is given by:

$$SVF = \cos^2\theta \qquad \text{(Marks and Dozier, 1979)} \qquad (7)$$

where SVF = sky view factor,

$\theta$ = sky obstruction angle.

The sky obstruction angle is an average of the significant slope angles. The average angle was calculated to be $17.6^{o}$ relative to the mid-glacier observation point. Thus, the sky view factor is 0.9. Because sky view factor represents the unobscured sky fraction, $L_{SL}$ must be multiplied by (1- SVF). This term [$L_{SL}$ (1-SVF)], is only part of the total incoming hemispherical longwave flux, $L\downarrow$. This flux is symbolized as $L_{SL}\downarrow$. Next, the longwave contribution from the atmosphere alone, $L_A\downarrow$, must be determined. Although the atmosphere is quite transparent to shortwave radiation, it readily absorbs terrestrial radiation and, in turn, reradiates longwave radiation back to the surface (Sellers, 1965).

In evaluating the atmospheric flux, various models have been implemented which consist of theoretical and empirical formulae; some are based on statistical relationships between longwave radiation and measured meteorological variables. The underlying law in these formulas is again Stefan Boltzmann. A model had to be chosen which represented as much as possible similar climatological conditions to those in the Alaska Mountain Range. The empirical model of Suckling and Wolfe (1979) for Resolute, Canada (75°N) was selected. This is in proximity latitudinally to the Alaska Range at 65°N even though at much lower elevation.

The Suckling/Wolfe model is:

$$L_A\downarrow = \sigma T_a^4(.627 + .017\sqrt{e})(1 + dn^2) \qquad (10)$$

where $L_A\downarrow$ = incoming longwave flux from atmosphere,

$\sigma$ = Stefan Boltzman constant,

$T_a$ = screen level air temperature above glacier surface (°K),

$e$ = screen level vapor pressure of the air (mb),

$d$ = cloud type coefficient,

and $n$ = sky cover in tenths.

The magnitude of $L_A\downarrow$ depends primarily on the atmospheric temperature, amount and type of clouds, and water vapor in the air. Cloud cover and water vapor are important because they contribute to longwave absorption in the atmosphere, thus increasing the atmospheric emissivity. The atmospheric temperature and vapor pressure were measured at screen level approximately 1.5m above surface.

The vapor pressure was calculated using:

$$RH = e/e_s \qquad (11)$$

where $e$ = vapor pressure,

$e_s$ = saturation vapor pressure,

and $RH$ = relative humidity.

Saturation vapor pressure was determined using standard meteorological tables relating temperatures to saturation vapor pressure. Likewise, relative humidity was found using relative humidity charts relating observed wet and dry bulb temperatures to relative humidity.

The coefficients 0.627 and 0.17 in Equation 10 are empirical constants derived from regression analysis at the Resolute location. The cloud type coefficients have magnitudes related to the absorptive characteristics of the cloud and are given in Suckling and Wolfe (1979).

The value of $L_A\downarrow$ was calculated with equation 10, but like $L_{SL}\downarrow$, the atmospheric contribution represents only one component of the total incoming longwave radiation. Therefore, since $L_A\downarrow$, evaluated by Equation 10, represents the flux equivalent of the entire sky dome, it must be multiplied by the SVF(0.9). Now this scaled value is the approximate incoming longwave flux from the atmospheric portion of the sky dome.

The modeled $L\downarrow$ is now:

$$L\downarrow_{model} = (SVF)L_A\downarrow + (1 - SVF)(L_{SL}) \qquad (12)$$

From this total value, the relative contribution of the valley wall side slopes, the component of interest, may be analyzed. In addition, the $L\downarrow_{model}$ value can be compared to $L_{obs}\downarrow$ using direct measurements to ascertain its degree of accuracy on the West Gulkana Glacier.

## RESULTS AND CONCLUSIONS

The first result concerns how well the $L\downarrow_{model}$ fits the observed values for $L\downarrow$. As shown in Figure 3, the modeled values do not exactly coincide with observations. They do, however, follow the same trends. The average percent error between modeled and observed values during clear days is only about 13.9%; while for cloudy days, the average error is surprisingly low at 5.9%. However, extreme outliers are also evident. Therefore, it is concluded that the model for Resolute Canada fits reasonably well with the West Gulkana location. The reason that the values coincided more closely during cloudy conditions may be attributed to the more similar relationships of

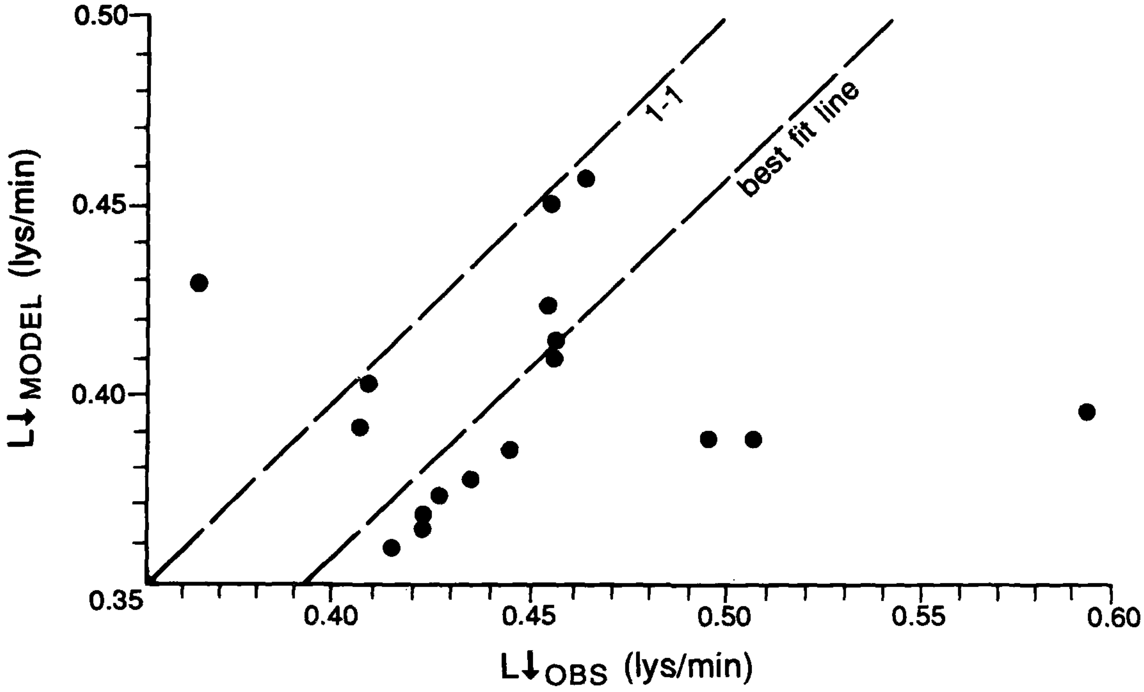


Figure 3. Scatter diagram and regression best-fit line for modelled and observed incoming long-wave radiation.

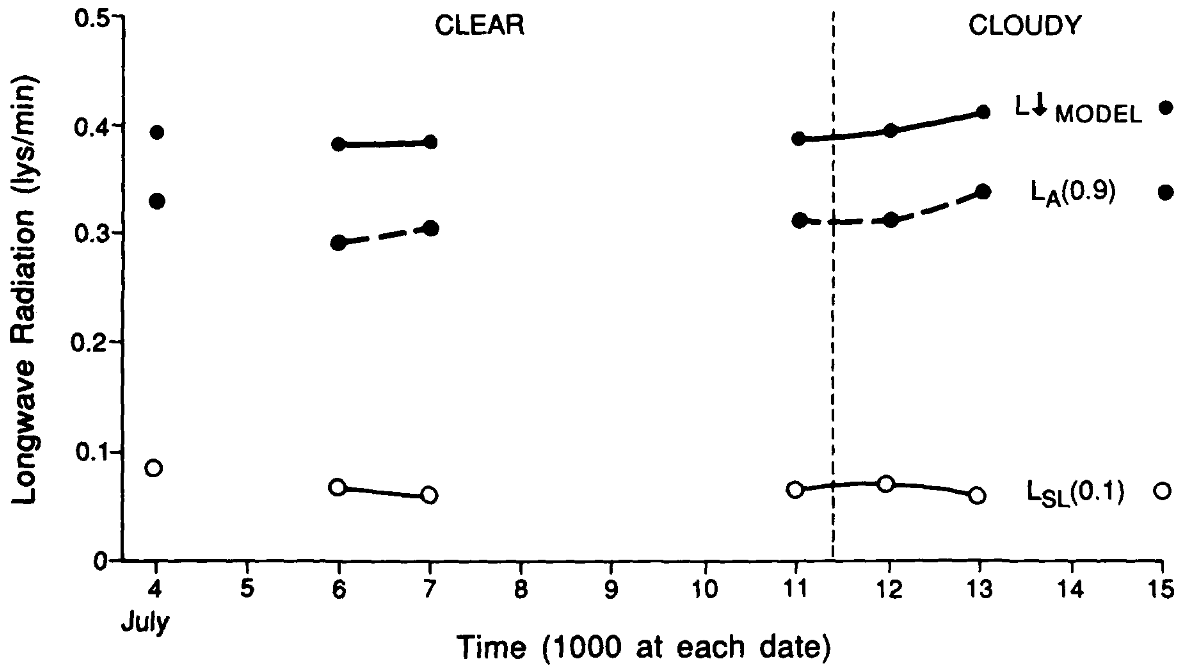


Figure 4. Observed and modelled long-wave radiation under clear and cloudy conditions.

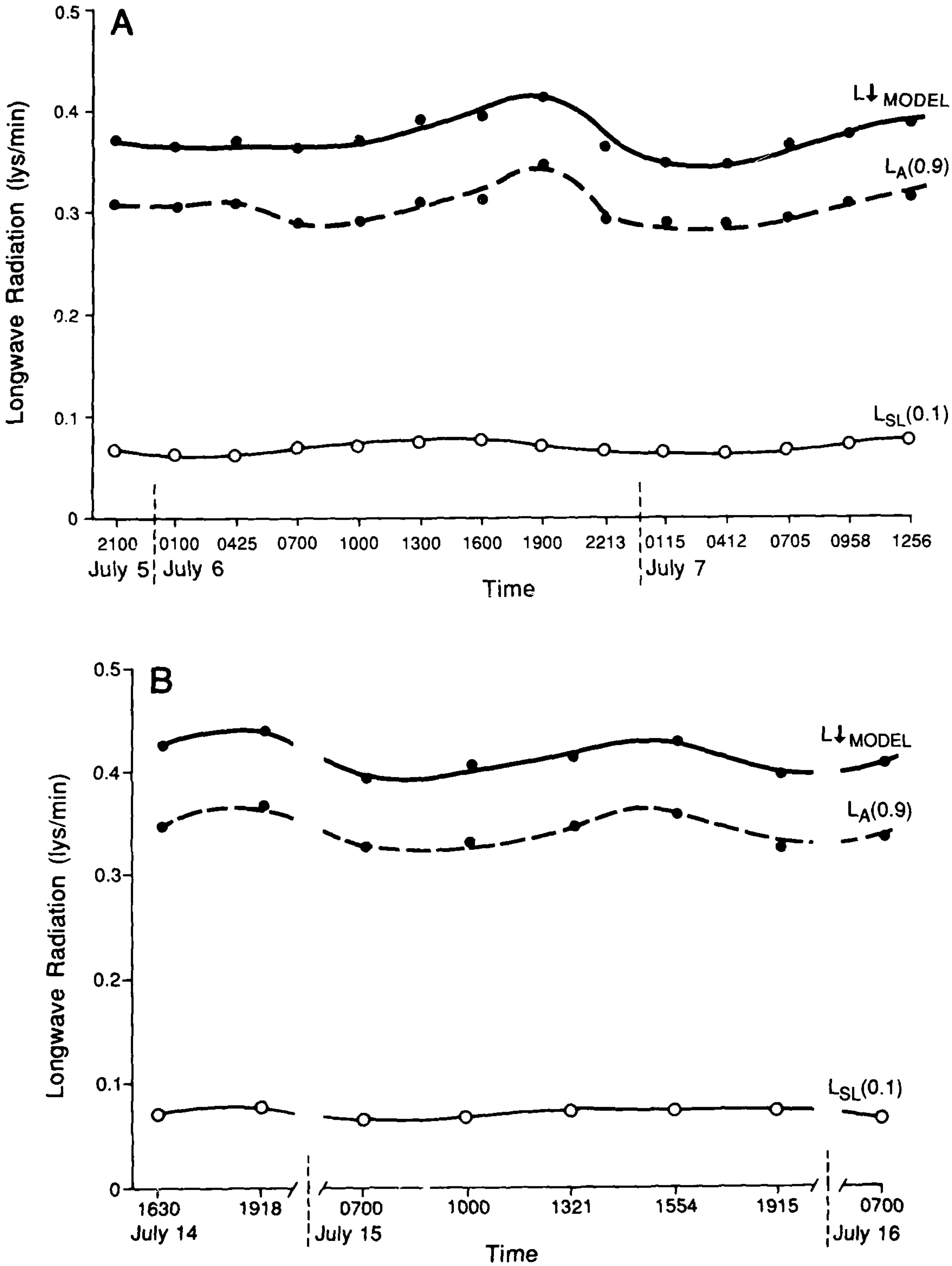


Figure 5. Incoming long-wave radiation under clear (5a) and cloudy conditions (5b).

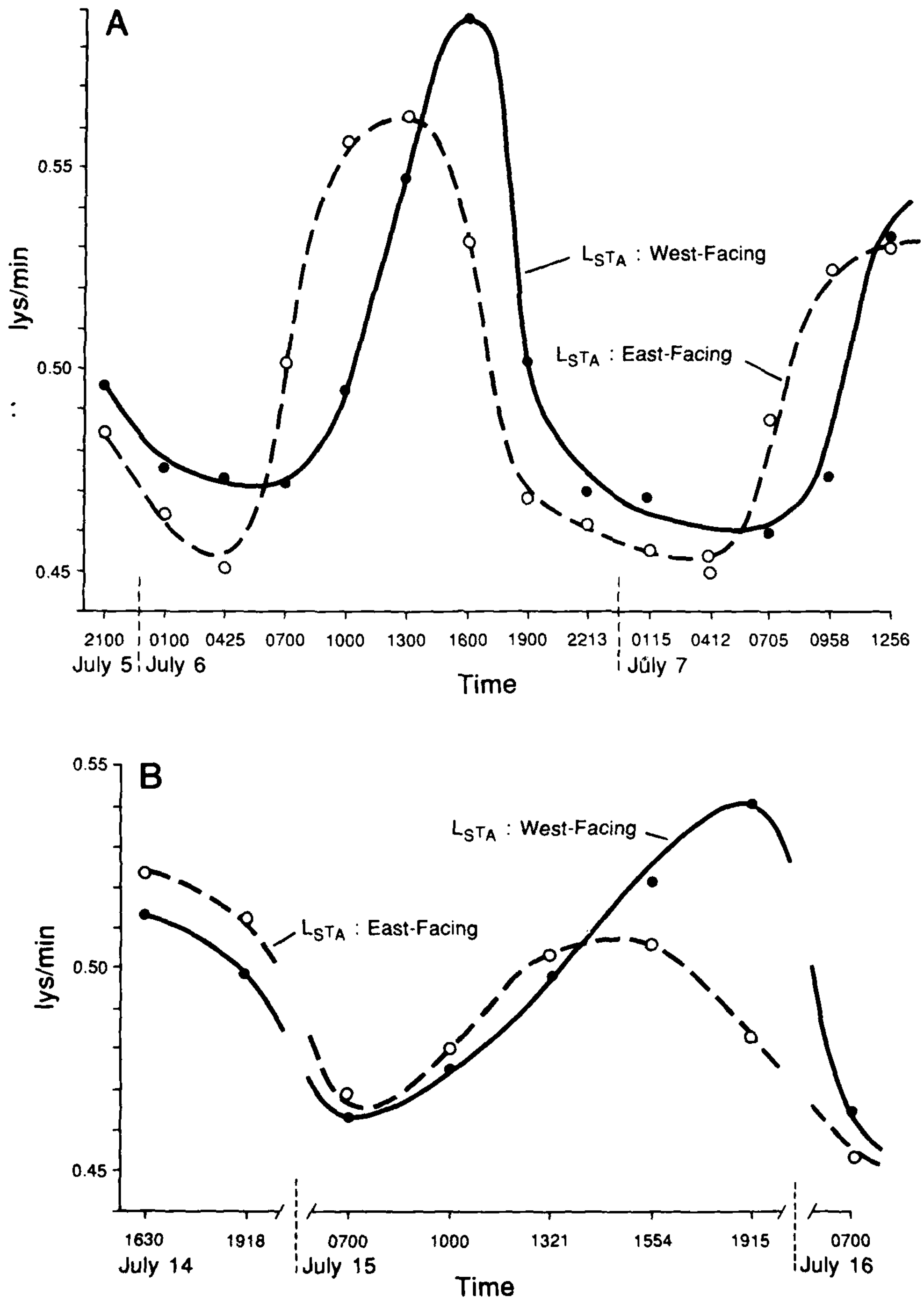


Figure 6. Long-wave emittance from east and west slopes on clear (6a) and cloudy (6b) days.

longwave radiation to vapor pressure and temperature parameters throughout deep layers of the atmosphere up to cloud bases. Also, during clear weather, strong inversions over the glacier surface may cause errors in empirical estimates (Miller, 1987).

As calculated from values shown in Figure 4, the percent of $L\downarrow$ that is $L_{SL}\downarrow$ ranges from 15.4 to 19.8%. However, because observations were made at mid-glacier, the maximum $L_{SL}\downarrow$ effect of the valley side walls on the margin of the glacier are probably underestimated.

For reasons of logistical limitations, longwave processes closer to the valley walls could not be observed. However, thermograph data from instruments situated on a moraine side wall showed days of air temperatures in excess of 21$^{o}$C. This site was less than 400 m from the glacier margin. These high wall air temperatures were consistent with remote IR temperature readings on clear days. Because the sky view factor decreases nearer the side slopes due to greater sky dome obstruction, the contribution of $L_{SL}\downarrow$ may subsequently increase above values estimated for mid-glacier and exceed 15-20%.

Referring to the graphs of $L_{SL}\downarrow$ and $L\downarrow$ through clear days (Figure 5a), the variance of $L_{SL}\downarrow$ through the day is as expected. The $L_{SL}\downarrow$ value slightly increases as the day progresses due to absorption of solar radiation on slopes. The $L_{SL}\downarrow$ flux peaks between 1600 and 1900 LST. As the sun sinks below the horizon and solar radiation becomes negligible, the slopes radiate at increasingly lower rates as the rocks become cooler. It must be remembered, however, that the 0$^{o}$C snow fraction dampens the $L_{SL}\downarrow$ curve. For atmospheric $L_{A}\downarrow$ and combined $L_{obs}\downarrow$, values also peak at similar times, primarily forced by air temperature. Curves are similar on cloudy and clear days (Figure 5b).

If the values of $L_{STA}$ for each wall are compared on clear and cloudy days, some further interesting trends are displayed (Figure 6a and b). For clear conditions, the east-facing slopes have a larger flux output in the early morning than do west-facing slopes, due to the fact that they receive solar radiation early in the day. The east-facing flux peaks close to midday, whereupon the west-facing slopes assume prominence. In the early morning, these slopes were in the shade, but experience maximum solar load in the afternoon. The period of maximum radiation flux is thus related to the sun's intensity and the favorableness of the angle of incidence of the sun's rays on the side wall slopes. The value for both slopes gradually becomes approximately equal during the early morning hours, about 0500, as the nighttime absence of solar radiation causes cumulative radiative cooling. Clouds tend to reduce the variations in emitted longwave radiation due to absorption of incoming solar radiation. However, the flux peaks of east- and west-facing walls still occur approximately at the same times as on clear days (see Figure 6b). West facing slopes have the higher peak because they receive maximum solar load during the afternoon at the highest ambient temperature time.

## SUMMARY

Incoming longwave flux from valley walls adjacent to the glacier constitute a *significant* portion of the total incoming longwave flux, even at mid-glacier locales. This finding is consistent with other studies in alpine and/or glacier environments (Olyphant, 1986; Marcus, et al., 1981; and Brazel and Marcus, 1987). Future longwave emittance studies in this type of environment should include heating processes at the glacier margins, development of a model of $L\downarrow$ for the entire area of the West Gulkana glacier, and observations of processes over a longer period.

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## SYMBOLS USED IN TEXT

d = Cloud Type Coefficient *(after Suckling and Wolfe)*

e = Screen level vapor pressure of air (mb)

$e_s$ = Saturation vapor pressure of air (mb)

fr = Fraction of slope target area that is rock surface

fs = Fraction of slope target area that is snow covered

G = Subsurface heat flux

H = Sensible heat flux

$L\downarrow$ = Total incoming longwave radiation

$L_A\downarrow$ = Atmospheric portion of total incoming longwave radiation

$L\downarrow_{model}$ = Modeled total incoming longwave radiation

$L\downarrow_{obs}$ = Measured total incoming longwave radiation (indirect)

$L_{SL}\downarrow$ = Slope terrain portion of total incoming longwave radiation

$L_{ESTA}$ = Longwave emittance from east slope target area i

$L_{SL}$ = Longwave emittance measured from all target slopes

$L_{STA}$ = Longwave emittance from slope target area

$L_{WSTA}$ = Longwave emittance from west slope target areas j

$L\uparrow$ =Emitted longwave radiation from mid-glacier snow/ice

LE = Latent heat flux

M = Melt heat equivalent

n = Sky cover (in tenths)

P = Heat of melt from rainfall

RH = Relative humidity

$R_n$ = Net radiation balance

$S\downarrow$ = Total incoming shortwave radiation

$S\uparrow$ = Total reflected shortwave radiation

SVF = Sky view factor

$T_s$ = Snow/ice surface temperature ($^oK$)

$T_{sl}$ = Aggregate IR apparent temperature of slopes ($^oK$)

$T_r$ = Apparent IR rock surface temperature on slopes ($^oK$)

$T_a$ = Screen height air temperature ($^oK$) at mid-glacier

$\alpha$ = Surface albedo

$\varepsilon$ = Emissivity

$\mu m$ = Micrometers

$\varepsilon_s$ = Snow emissivity

$\varepsilon_r$ = Rock emissivity

$\theta$ = Sky obstruction angle

## AIR TEMPERATURE VARIATIONS OVER DIFFERENT SURFACES IN THE WEST GULKANA GLACIER VALLEY

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### INTRODUCTION

As part of summer 1986 and 1987 meteorological and glaciological observations on West Gulkana Glacier, several hygrothermographs were positioned over various surfaces in order to study the magnitude of meso-scale temperature and humidity variations under differing weather conditions. These short-term observations provide insights: (1) to spatial variations of glacier ablation and surface snowmelt; (2) to the representativeness of the full-summer meteorological stations on the glacier (1986) and at the tundra station (1987); and (3) to the contribution of various surface types to a valley-integrated energy budget regime. In this paper, only temperature data are analyzed.

### DATA COLLECTION AND ANALYSIS

Three locations were chosen for the establishment of hygrothermograph stations in 1986: (1) the main glacier meteorological station in the center of the West Gulkana Glacier (see Brazel, Marcus, and Moore, this volume); (2) a west-facing lateral moraine location 400 m east of the glacier site and 30 m above the glacier surface (see Henderson, Brazel, and Reynolds, this volume), and (3) a location on terminal moraine, some 50 m from the ice tongue. The length of record at these sites are June 20 - July 27, July 2 - July 20, and June 22 - July 20, 1986, respectively. All sites were visited weekly and hygrothermographs were checked periodically for calibration and adjusted when necessary. In conjunction with the glacier and terminus hygrothermographs, actinographs tracked incoming solar radiation on a continuous basis.

Two stations were installed during 1987: (1) a tundra location at elevation 1265 m, some 230 m lower than the glacier station of 1986; and (2) a re-established terminus station. The period of records were June 27 - July 26 and June 28 - July 25, 1987, respectively. Continuous recordings of incoming solar radiation were maintained at the tundra site and terminus site during these times. All hygrothermographs were housed in similarly-designed meteorological shelters and elevated 1.5 m above the immediate surface.

For this paper, several sample days from each year were selected to provide insight into the variation of air temperature during clear/partly cloudy and cloudy situations. Inspection of the standard meteorological observations, actinograph charts from 1986 and 1987, and a quality check of all data resulted in the selection of 5 days in 1986 and 8 days in 1987 (see Table 1). These days were chosen to optimize comparisons at the four sites in respective years under clear/partly cloudy and cloudy periods.

## RESULTS

Table 2 summarizes the total sample days extracted from the two study years. Figures 1, 3, and 5 present selected hygrothermograph traces for different surfaces. Figures 2 and 4 are actinograph traces for the glacier site; Figure 6 is for the tundra site. From Table 2, note the differences in the station intercomparisons between clear/partly cloudy and cloudy weather conditions. For 1986, there is a range from 8 to 13$^{o}$F for maximum temperature differences among sites on clear/partly cloudy days. Interestingly, the terminus site and the mid-glacier site experience similar average maximum and minimum temperatures for the three days chosen.

Depending on the nature of the snow surface at the terminus, however, different relationships result. On June 23, a period immediately after a major, valley-wide snowfall and early in the melt season, the glacier site is warmer, but on June 30

**TABLE 1**

**DAYS SELECTED FOR TEMPERATURE ANALYSIS***

| Weather | WFM (1986) | Glac (1986) | Term (1986) | Tundra (1987) | Term (1987) |
|---|---|---|---|---|---|
| Clear/Partly Cloudy | -- | 6-23 | 6-23 | | |
| | -- | 6-30 | 6-30 | 6-30 | 6-30 |
| | 7-6 | 7-6 | 7-6 | | |
| | | | | 7-9 | 7-9 |
| | | | | 7-10 | 7-10 |
| | | | | 7-20 | 7-20 |
| | | | | 7-21 | 7-21 |
| Cloudy: | 7-8 | 7-8 | 7-8 | | |
| | 7-13 | 7-13 | 7-13 | | |
| | | | | 7-14 | 7-14 |
| | | | | 7-15 | 7-15 |
| | | | | 7-22 | 7-22 |

*For detailed weather conditions of these days, see Marcus, Brazel, and Moore (elsewhere in this volume).

WFM = West-facing moraine site
Glac = mid-glacier meteorological site
Term = Terminus site below glacier
Tundra = Tundra site

and July 6 maximum temperatures during the day are considerably warmer on the glacier terminus moraine surface than on the glacier. At these times the terminus site was snow-free, exposing dark moraine. For the one clear period at all three sites (July 6), a particularly warm maximum temperature is indicated for the west-facing, moraine location.

TABLE 2

COMPARATIVE MAXIMUM AND MINIMUM TEMPERATURES (in $^{o}F$) FOR SAMPLE DAYS SHOWN IN TABLE 1*

1986 Clear/Partly Cloudy Days

| | WFM | | Glac | | Term | |
|---|---|---|---|---|---|---|
| | Mx | Mn | Mx | Mn | Mx | Mn |
| 6-23 | -- | -- | 54 | 35 | 41 | 31 |
| 6-30 | -- | -- | 56 | 36 | 64 | 42 |
| 7-6 | 68 | 44 | 56 | 40 | 64 | 35 |
| Mean | | | 55 | 37 | 56 | 36 |

1986 Cloudy Days

| | WFM | | Glac | | Term | |
|---|---|---|---|---|---|---|
| | Mx | Mn | Mx | Mn | Mx | Mn |
| 7-8 | 46 | 39 | 44 | 34 | 46 | 42 |
| 7-13 | 39 | 35 | 38 | 34 | 48 | 41 |
| Mean | 43 | 37 | 41 | 34 | 47 | 42 |

1987 Clear/Partly Cloudy Days

| | Tundra | | Term | |
|---|---|---|---|---|
| | Mx | Mn | Mx | Mn |
| 6-30 | 68 | 38 | 50 | 40 |
| 7-9 | 66 | 36 | 47 | 38 |
| 7-10 | 65 | 35 | 50 | 39 |
| 7-20 | 73 | 52 | 66 | 40 |
| 7-21 | 72 | 49 | 52 | 40 |
| Mean | 69 | 42 | 53 | 39 |

1987 Cloudy Days

| | Tundra | | Term | |
|---|---|---|---|---|
| | Mx | Mn | Mx | Mn |
| 7-14 | 50 | 44 | 45 | 37 |
| 7-15 | 51 | 45 | 46 | 37 |
| 7-22 | 56 | 44 | 50 | 38 |
| Mean | 52 | 44 | 47 | 37 |

During cloudy weather, variations among sites are less and local maxima in temperature are hard to explain, but probably relate to local sun exposure differences due to differences in cloudiness. In addition, elevational changes may have an effect.

For 1987, the terminus site is compared with the tundra location. The tundra site is farther downvalley and on a bench situated on the east side of the valley, away from the immediate effects of the cold glacier surface and cold drainage. There are large differences in maximum temperatures for clear weather, ranging from 7 to 20$^{o}$F. Tundra heating appears more effective than heating over the dark terminus moraine site. This was no doubt abetted by long-lasting snow near the terminus in 1987; however, even near the season's end, there is a large difference in maximum temperature (e.g., July 21). The terminus receives cool air from the glacier, contains snowmelt and stream-derived moisture, and has a large heat capacity in comparison to the spongy, organic, insulating mat of tundra vegetation.

During cloudy weather, the differences in temperature are similar to the differences observed among the sites sampled in 1986. Although the two field seasons were not identical in overall temperature averages (see Marcus, Brazel, and Moore, this volume), there is remarkable comparability in temperatures recorded at the terminus site for the clear and cloudy samples selected from 1986-87. This allows for a comparison of the 1986 sites with the tundra site in Table 2.

The West-facing moraine site, at a higher elevation than the tundra site, records similarly high maximum temperatures, mostly due to the increased solar load it enjoys during the afternoon hours. For cloudy weather conditions, it is likely that the tundra site is warmer because of its location closer to the outlet of the valley, at lower elevation, and away from local dense clouds forming in the upper areas of the valley and over the glacier.

## DIURNAL COMPARISONS

Three diurnal periods are shown to illustrate further temperature relationships. The three cases are June 23 and July 6, 1986 and July 21, 1987. In the June 23rd case, the mid-glacier site is compared with the terminus location (Figures 1 and 2). At this time virtually the entire West Gulkana glacier valley was snow-covered. By July 6, 1986 the terminus site was snow-free and the glacier site was on the boundary of melting snow, slush, and exposed glacier ice. Figure 3 and 4 represent the temperature comparisons and solar radiation for this day. Figures 5 and 6 illustrate general comparisons between the tundra and terminus sites during clear weather late in the summer of 1987.

**JUNE 23, 1986**

Comparing the glacier and snow-covered terminus sites, the glacier temperatures are warmer by $4^{O}F$ at night until about 0800 LST (Figure 1). The glacier temperatures increase to $8\text{-}18^{O}F$ warmer than the terminus during daytime hours. On this day, a thin veil of cloud hovered over the glacier following a major snowstorm. Winds were light during the daytime. The unusually warm temperatures on the glacier (compared to the terminus) during the day may relate to solar absorption within the diffusing fog bank on the glacier and meteorological shelter warming. Drainage of air downglacier probably accounts for the cooler temperatures at night at the terminus. These conditions on the 23rd appear to be unusual; but, in fact, separate inspection of June 24 - 30 temperatures indicate that temperatures remained generally warmer on the glacier compared to the terminus locale until the month's end, when clear weather melted snow off the glacier terminus.

**JULY 6th, 1986**

By July 6, snow had melted off the terminus area and the snowline on the glacier was close to the elevation of the main glacier meteorological station (c. 1500 m). By this time the lateral west-facing moraine east of the glacier site was relatively snow-free and a hygrothermograph was established above

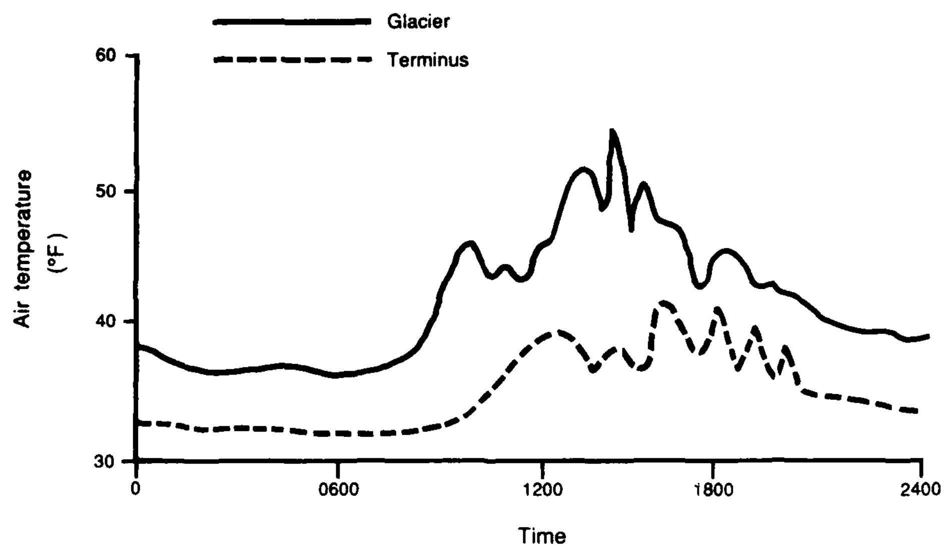


Figure 1. Diurnal air temperature for glacier and terminus stations, June 23, 1986.

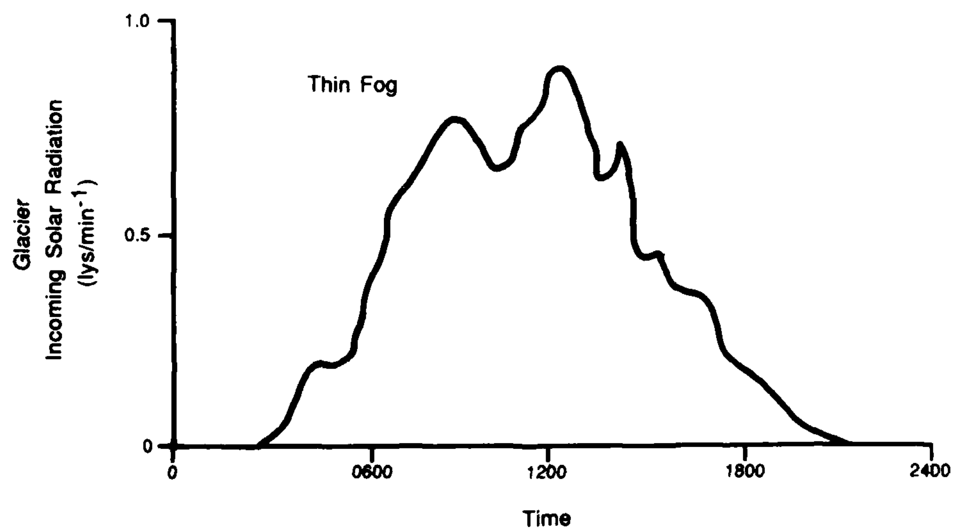


Figure 2. Actinograph (solar radiation) trace at glacier station, June 23, 1986.

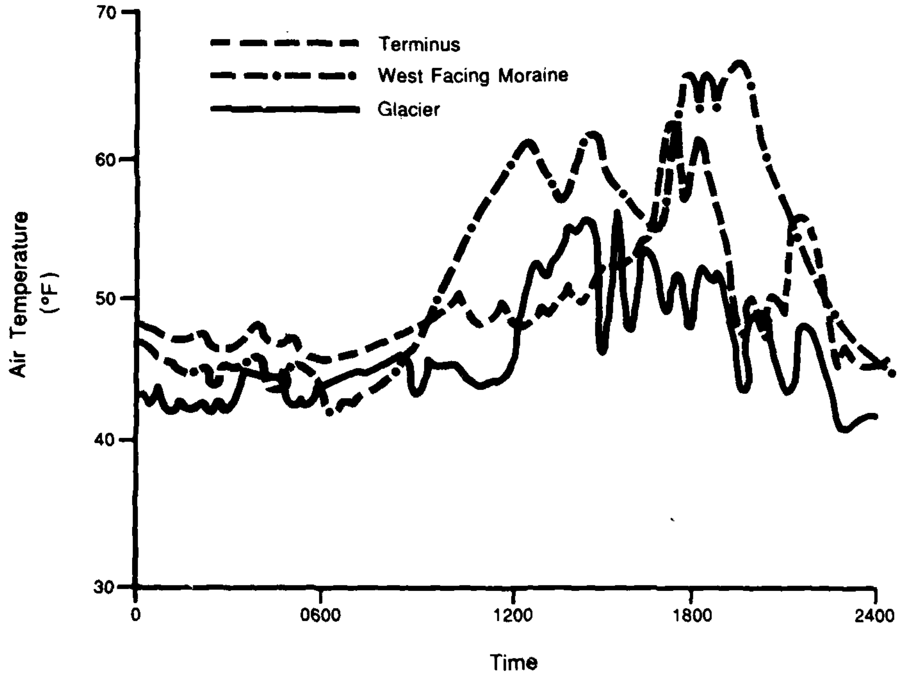


Figure 3. Air temperatures at west facing moraine, glacier, and terminus sites, July 6, 1986.

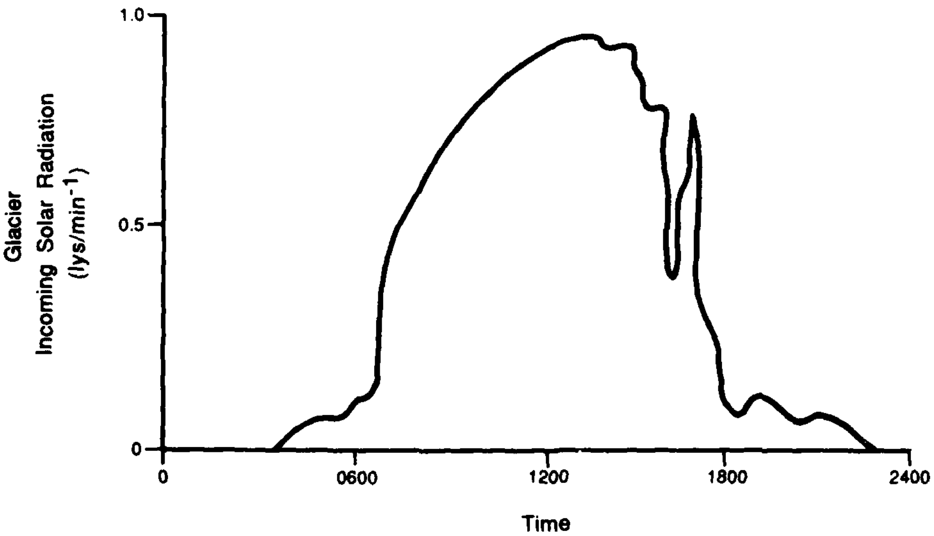


**Figure 4.** Actinograph (solar radiation) trace at glacier station, July 6, 1986.

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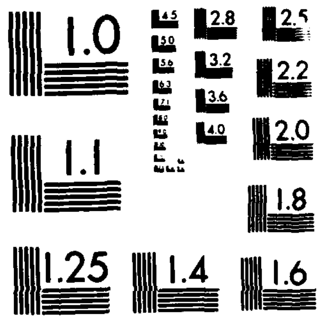


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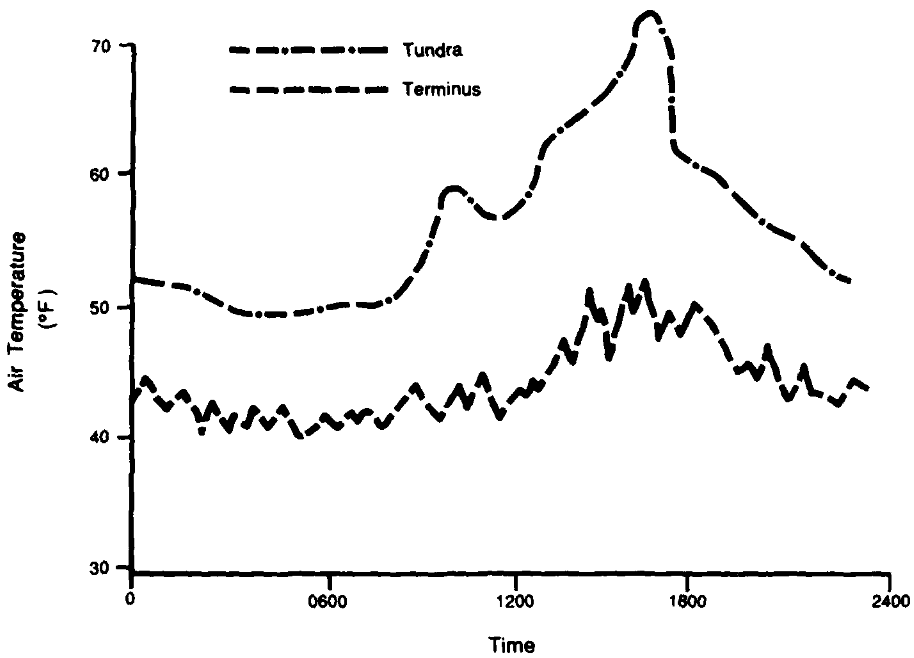


Figure 5. Air temperatures at tundra and terminus, July 21, 1987.

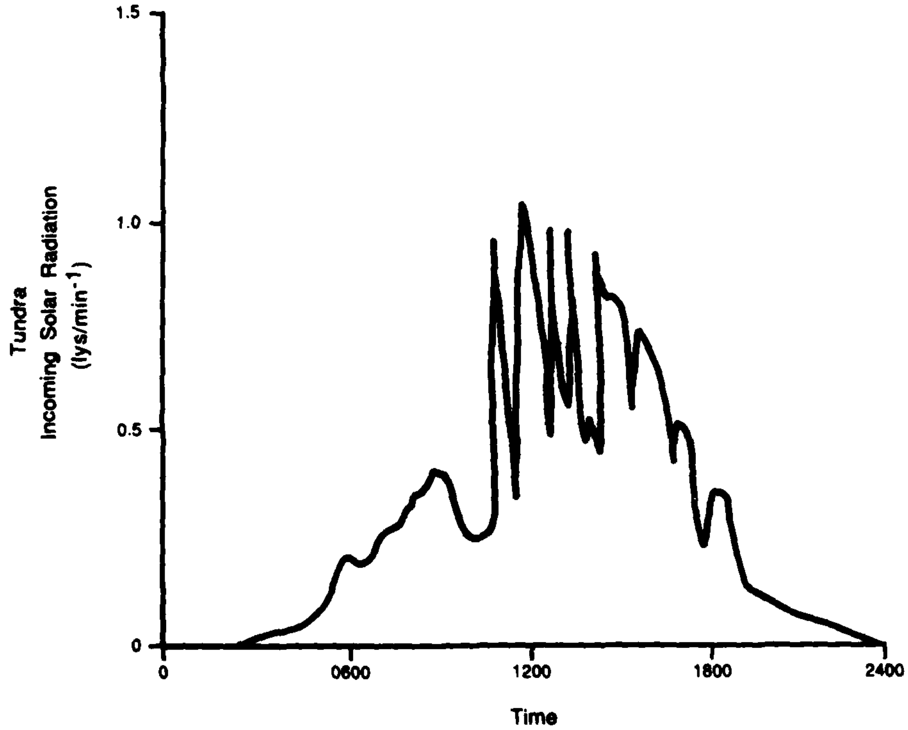


Figure 6. Actinograph (solar radiation) trace for tundra site, July 21, 1987.

the glacier surface on the moraine. All three sites can be compared for this day. The day consisted of mostly clear skies and down glacier winds. Slush avalanches were observed just west of the main glacier observation station.

Figure 3 shows the thermograph traces for the west-facing moraine (WFM), the glacier site, (GLAC) and the terminus (TERM) location. The west-facing moraine site is about the same temperature as the glacier station at 0600 LST. The glacier temperatures warm to slightly greater values than the moraine site until 1000 LST, since the moraine is west-facing and still in shade. After 1000 LST, the moraine site warms rapidly, peaking in late afternoon at 1800 LST.

There are large short-term variations in temperature on the glacier and less inter-hourly variation on the moraine. The large fluctuations on the glacier are associated with variable wind velocities. Wind pulses were continually observed on the glacier during the daytime; these pulses were not as obvious at the higher moraine elevations next to the glacier. These pulses are also evident upon comparing the glacier with the terminus location. The terminus is about $4^{\circ}F$ warmer than the glacier site until noon. Cold air pulses commence at this time and result in cooling the lower terminus location to a temperature below that of the glacier site. This cooling lasts until 1500 LST. The actinograph (Figure 4) trace indicates cloud effects after this time, and the glacier cools down in comparison to the terminus location. The effect of regional variations in clouds experienced at both sites is evident at 2100 LST. Thereafter, the glacier is once again consistently cooler than the terminus by $4^{\circ}F$. The large temperature fluctuation at both sites at 2100 LST corresponded to a thunderstorm moving over the valley from the southeast. Clear skies prevailed after this time for the rest of the night.

## JULY 21, 1987

A comparison of tundra and terminus sites is shown in Figure 5. On this day, partly cloudy skies prevailed, with some rain early in the day and generally clearing skies in the afternoon (see actinograph trace, Figure 6). At night the terminus is cooler by 8°F. The terminus site is in the valley and below the glacier, thus experiencing glacier wind effects. During daylight hours, the tundra site heats dramatically to about 20°F warmer than the terminus location. Although rock moraine fragments exposed to direct sunlight should heat to a temperature not that different from tundra vegetation, the moraine complex is greatly affected by surface moisture and downglacier flow, as suggested earlier. Also, the terminus temperature trace reveals a wind-pulse pattern.

## CONCLUSIONS

Considerable spatial variability, dependent on surface conditions, is shown by this preliminary analysis of comparative hygrothermograph sites in the West Gulkana Valley. As surface conditions change over the summer season, there is a detectable change in the thermal pattern within the valley. Slope, exposure, proximity to glacier wind effects, and surface/subsurface material control the temperature patterns over the summer in this environment. The differences are maximized under clear skies and calmer conditions.

Temperature characteristics indicated by the thermograph data set suggest that careful consideration should be given to specific placement of stations in any glacier ablation study. A clearer characterization of the spatial temperature field in glacier valleys is needed and requires an appropriate station network design to comprehensively sample climatic effects.

The limited degree of correlation between glacier temperatures and upper level temperatures and cloudiness (see Brazel, this volume) can partially be attributed to inherent problems with point sampling of spatially variant temperatures across complex alpine terrain. Attempts to extrapolate glacier climate parameters from remote sites or upper level soundings must be based on sound analyses of relationships of point samples to areal variability of these parameters.

# ASPECTS OF WIND ON WEST GULKANA GLACIER, ALASKA

by

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Wind observations on West Gulkana Glacier were taken as part of standard measurements at the main meteorological station (1495 m) during the 1986 field season (Brazel, Marcus, and Moore, this volume). These data were taken primarily at daytime synoptic hours. This paper summarizes wind data for 0000Z (1600 Local Alaskan Time) in order to compare upper air patterns (850 and 500 mb) to surface winds experienced on the glacier and at Summit Lake. Results from a spatial sampling of winds across the glacier are also presented.

## DATA ANALYZED

Table 1 presents a data summary of wind for the period 21 June to 18 July, 1986. Although a survey party remained on the glacier eight days after July 18th, no systematic wind observations are available; however, a major storm did affect operations during that time and maps of the synoptic situation are presented in addition to those from the 21 June - 18 July period. Table 1 shows: (1) wind velocity and direction at mid-glacier at 1600 hours LST; (2) wind velocity and direction at 1600 LST as recorded at Summit Lake Lodge (Brazel, Buckley, and Strauss; this volume); and (3) interpolations of wind direction and velocity for the West Gulkana location at 850 and 500 mb levels based on 0000Z observations for Anchorage and Fairbanks. Table 1 also includes cloud cover direction as observed from the

TABLE 1

WIND VELOCITY AND DIRECTION FOR 1600 LST AT
WEST GULKANA GLACIER, SUMMIT LAKE LODGE, AND FREE AIR*
FOR SUMMER SEASON, 1986

| | Glacier | | Summit | | 850 mb | | 500 mb | | Glacier | |
|---|---|---|---|---|---|---|---|---|---|---|
| | v | d | v | d | v | d | v | d | Cloud | cd |
| 21 June | 1.6 | N | 0.0 | SW | 5.0 | SSE | 5.8 | SE | 10 | E |
| 22 | 1.9 | N | 0.0 | NE | 5.0 | SW | 5.0 | SE | 10 | W |
| 23 | 0.8 | NNW | 0.3 | SSW | 8.9 | WSW | 7.7 | ENE | 10 | - |
| 24 | 0.8 | NNW | 2.9 | W | 7.7 | SW | 6.5 | S | 8 | W |
| 25 | 1.3 | NNW | 0.9 | N | 5.1 | SSW | 9.1 | W | 10 | W |
| 26 | 1.8 | NNW | 0.3 | S | 6.5 | SSE | 9.1 | SSW | 2 | SW |
| 27 | 3.8 | NNW | 4.2 | S | 6.4 | S | 12.9 | SSW | 1 | W |
| 28 | 3.9 | NNW | 2.1 | E | 6.5 | SE | 11.6 | SSE | 4 | SE |
| 29 | 4.6 | NNW | 0.8 | N | 3.8 | ESE | 8.9 | SE | 1 | S |
| 30 | 4.1 | NNW | 3.9 | N | 3.8 | ENE | 9.1 | SE | 1 | E |
| 1 July | 3.9 | NW** | 4.9 | S | 2.9 | NE | 10.3 | SE | 5 | SE |
| 2 | 6.2 | NNW | 0.7 | N | 5.1 | E | 6.5 | NE | 3 | SE |
| 3 | 2.8 | NNW | 5.0 | NW | 2.5 | NE | 1.2 | N | 7 | E |
| 4 | 2.6 | N | 0.4 | NE | 5.1 | NW | 3.8 | NW | 7 | NW |
| 5 | 4.6 | NNW | 0.8 | E | 3.8 | SE | 8.9 | SE | 5 | S |
| 6 | 4.7 | NNW | 2.7 | S | 5.1 | SE | 11.5 | ESE | 3 | SE |
| 7 | 3.2 | NW | 7.4 | W | 3.8 | SE | 14.1 | ESE | 9 | E |
| 8 | 1.5 | NW | 0.0 | N | 2.5 | W | 6.5 | SE | 10 | N |
| 9 | 2.8 | NW | 8.9 | NE | 5.1 | NE | 5.1 | SSE | 6 | S |
| 10 | 6.1 | N | 10.1 | NW | 12.7 | W | 2.5 | S | 2 | SE |
| 11 | 4.7 | NNW | 8.8 | SE | 5.1 | SW | 10.3 | SW | 10 | N |
| 12 | 2.8 | E | 2.7 | NW | 2.5 | E | 10.3 | S | 10 | SE |
| 13 | 2.3 | S | 7.4 | NE | 5.1 | S | 5.1 | SE | 10 | NW |
| 14 | 0.6 | NNW | 1.1 | NNE | 2.5 | NE | 7.8 | S | 8 | S |
| 15 | 3.0 | S | 6.4 | NW | 9.1 | SSE | 16.8 | SW | 9 | S |
| 16 | 4.5 | N | 4.5 | SE | 5.1 | N | 12.9 | SSE | 5 | SE |
| 17 | 3.9 | NE | 7.2 | -- | 3.9 | E | 9.1 | S | 3 | SE |
| 18 | 3.7 | NNW | 5.9 | -- | 5.1 | SW | 10.3 | W | 10 | W |
| Mean | 3.7 | | 3.6 | | 5.2 | | 8.5 | | 6.4 | |

* Interpolated winds from Anchorage/Fairbanks soundings at 0000Z.
** The actual direction for a moment on the hour of 1600 was SW, but during the entire period prior to and after 1600, the wind was down-glacier from NW.
v = wind velocity in msec $^{-1}$.
d = wind direction.
cloud = tenths of cloud cover over glacier site.
cd = direction from which clouds are moving.

glacier weather station.

The National Climatic Data Center maps of 500 mb geopotential heights and winds and 850 mb wind patterns were interpreted. The 1986 summer patterns for 1600 LST are depicted in a series of figures under the umbrella of Figures 1 and 2 at the end of this article. These maps are used to compare motion patterns in the free atmosphere with winds on the glacier. For the 850 mb maps, wind vectors are shown coded by the standard speed categories of the station model on weather maps (Figure 1). The glacier vector is indicated at the black square in each figure. Wind vectors are similarly shown for the 500 mb map and a contoured geopotential height pattern is illustrated and labeled in decameters. Positions of low and high heights of the 500 mb surface are also labeled for the region (Figure 2).

## RESULTS OF THE WIND ANALYSIS

Table 1 reveals several interesting aspects of the West Gulkana wind regime (see Frontispiece for general orientation of the glacier and its environs). Wind direction shows a strong northerly and westerly component throughout the season--primarily down-glacier. The wind directions experienced at nearby Summit Lake Lodge, out of the glacier environment, are contrary to the down-glacier wind direction more than 50 % of the time. Also, cloud directions, as observed from mid-glacier, are almost never in the same direction as the wind observed on the glacier. This illustrates the typical channeling effect of the glacier valley and strong drainage wind effects evident on the West Gulkana.

The 850 mb wind directions for the West Gulkana locale agree with glacier surface wind vectors on ten occasions. Some of these cases were characterized by very gusty and rotor-like winds at mid-glacier. Four extremely gusty wind periods were experienced during the short sampling period (1, 10, 15, and 18 July); only on July 1 were wind directions at 850 mb generally similar to those on the glacier.

Wind speeds on the glacier were almost always less than the interpolated 850 mb winds. The exception was the period June 29 to July 5th, when glacier winds were higher than the free air 850 mb flow. Wind directions aloft were somewhat in alignment with the down-glacier direction during most of this time period (Figure 1), thus inducing acceleration of a katabatic-like flow down the glacier. The only other substantive agreement between glacier valley flow direction and upper level was during 12-17 July (Figure 1). Winds on the glacier were generally less than those aloft at the 850 mb level during this time. Only on the 14th were upper level winds at 850 mb in a down-glacier direction. Thus, upper level support of a down-glacier flow regime were, for the most part, absent during this period.

After the 18th of July, workers who remained on the glacier experienced the highest winds of the entire summer observation period. No detailed measurements of winds at mid-glacier were made during this time due to the severely hazardous conditions. However, inspection of the 850 and 500 mb sequence from the 18th to the end of the period indicates that wind flow was greatest of the summer observation period and height gradients at 500 mb were steepest across the Central Alaskan region during the post 18 July period (Figure 2). Wind velocity at 500 mb exceeded 26 $msec^{-1}$. Winds at 850 mb topped 16 $msec^{-1}$. Gusts were probably double these values. Personnel on the glacier took spot observations of wind over several minutes and observed a steady wind velocity of 22.5 $msec^{-1}$, with possible gusts exceeding 36 $msec^{-1}$. During this time a large pressure gradient developed between low pressure in Northern Alaska and an intruding high pressure pushing eastward from the Aleutian Island region. From the 21st to 23rd, a large, deep trough in Western Alaska developed and increased the upper level wind flow from the southwest (Figure 2).

## LOCAL GLACIER WIND VARIATIONS

Wind measurements were restricted to the main glacier meteorological site for most of the field season. For a one day period, however, anemometers were available to sample wind variations at several locations on the glacier surface. A survey of winds was conducted on 26 June, 1986 from 0700 to 1900 LST. The weather was clear and calm, with winds generally downglacier all day. A T-array of sample points was established on the glacier, with the meteorological station constituting the center of the top of the T. The other three sites were positioned relative to the meteorological site as indicated in Table 2.

**TABLE 2**

**GLACIER WIND SAMPLE SITES, 26 JUNE, 1986**

| Wind Sites | Characteristics | Slope | Elevation |
|---|---|---|---|
| Meteorological Site | snow surface flat | $4.6^{\circ}$ | 1495 m |
| Western | snow surface flat | $5.1^{\circ}$ | 1495 m |
| Eastern | snow surface in swale | $5.1^{\circ}$ | 1480 m |
| Southern | snow surface flat | $6.8^{\circ}$ | 1430 m |

In a T-array: $\boxed{\text{Western}} \leftarrow 250\text{m} \rightarrow \boxed{\text{Mete. site}} \leftarrow 180\text{m} \rightarrow \boxed{\text{Eastern}}$

$\uparrow$ 430m $\downarrow$

$\boxed{\text{Southern}}$

The meteorological site (1495 m), the western site (1495 m) and the eastern site (1480 m) represent a transect of 430 m across the glacier surface. The southern site (1430 m) was 430 m directly downglacier from the meteorological site. The slopes of the glacier at the lateral axis sites were similar ($4.6$-$5.1^{\circ}$; the southern site was a bit steeper ($6.8^{\circ}$). On 26 June, the wind sample area was entirely snow covered. The eastern site was located on the edge of the glacier along the contact between the glacier and snow-covered moraine surface. The local topography consisted of a small valley oriented NW to SE with a slope of ca. 5 °. All the other sites were toward the center of the glacier and over 0.25 km from the glacier's edge.

**TABLE 3**

**WIND DATA FOR 26 JUNE, 1986**
(average in meters per sec)

| | Sites | | | | Wind Direction/time |
|---|---|---|---|---|---|
| Time | Mete. Site | Western | Southern | Eastern | (mete. site) |
| 07-10 | 1.34 | 1.79 | 1.47 | 1.47 | N (07) |
| 10-16 | 0.80 | 0.76 | 1.12 | 0.80 | N (10)<br>NNW (13) |
| 16-19 | 4.47 | 4.47 | 7.02 | 2.82 | NNW (16)<br>NNW (19) |
| Mean | 2.20 | 2.34 | 3.20 | 1.70 | |

Counter anemometers were positioned at a height of 1 m above the snow and were set in place by 0700. They were read at 1000, 1600, and 1900 LST during the day.

## RESULTS

Mean wind flow downglacier was light during this period (Table 3) and averaged from 1.7 to 3.2 msec$^{-1}$. This wind persisted during the day and is characteristic of a katabatic type glacier drainage wind. The wind flow strength of ca. 2.5 msec$^{-1}$ is almost exactly the downslope drainage wind velocity described by Streten and Wendler (1968) for the nearby Castner Glacier in the Alaskan Range. The West Gulkana downslope wind undergoes a diurnal velocity variation from moderately light in the early morning, almost calm around noon, and highest in mid-to-late afternoon. This pattern resembles behavior of the downglacier winds described for both the Worthington and Castner Glaciers (Streten and Wendler, 1968).

The strengthening of the downglacier flow in mid- to late afternoon relates to the time when the gradient of temperature between the cold glacier snow surface and free air might be expected to be at a maximum. This situation arises when there are light pressure gradients in the free atmosphere and diurnal variations in wind are attributed to local circulation set up by the contrast between the temperature of the snow surface and that of the free air at the same altitude (Streten and Wendler, 1968).

June 26th was characterized by the classic, light pressure gradient pattern described above (and indicated by the 500 mb geopotential height gradient shown in Figure 2 for June 26). Thus, even though the sample analyzed is limited, it probably represents a typical West Gulkana glacier downslope wind pattern, resembling wind regimes of many other glaciers.

Wind flow across and downglacier is expressed for the three sample times in Table 3. When wind direction is directly in line (i.e., NNW) with the long axis of the glacier, winds are fastest at the steeper, southern site. This would be expected, since the wind flow accelerates downglacier as slopes steepen. The slope between the meteorological site and the southern site increases by 1.8 $^{\circ}$ (Table 2). In the early morning, however, wind directions recorded at the main meteorological site were more directly from a northerly component. The highest average velocity was recorded at the western site. The fetch distance to the north to upper areas of the glacier from this point is greatest of any of the sites. The site with lowest overall speeds was the eastern site. An inspection of West Gulkana Glacier orientation (see frontispiece map) indicates that this site would be somewhat protected from winds of a northerly or north-northwesterly direction.

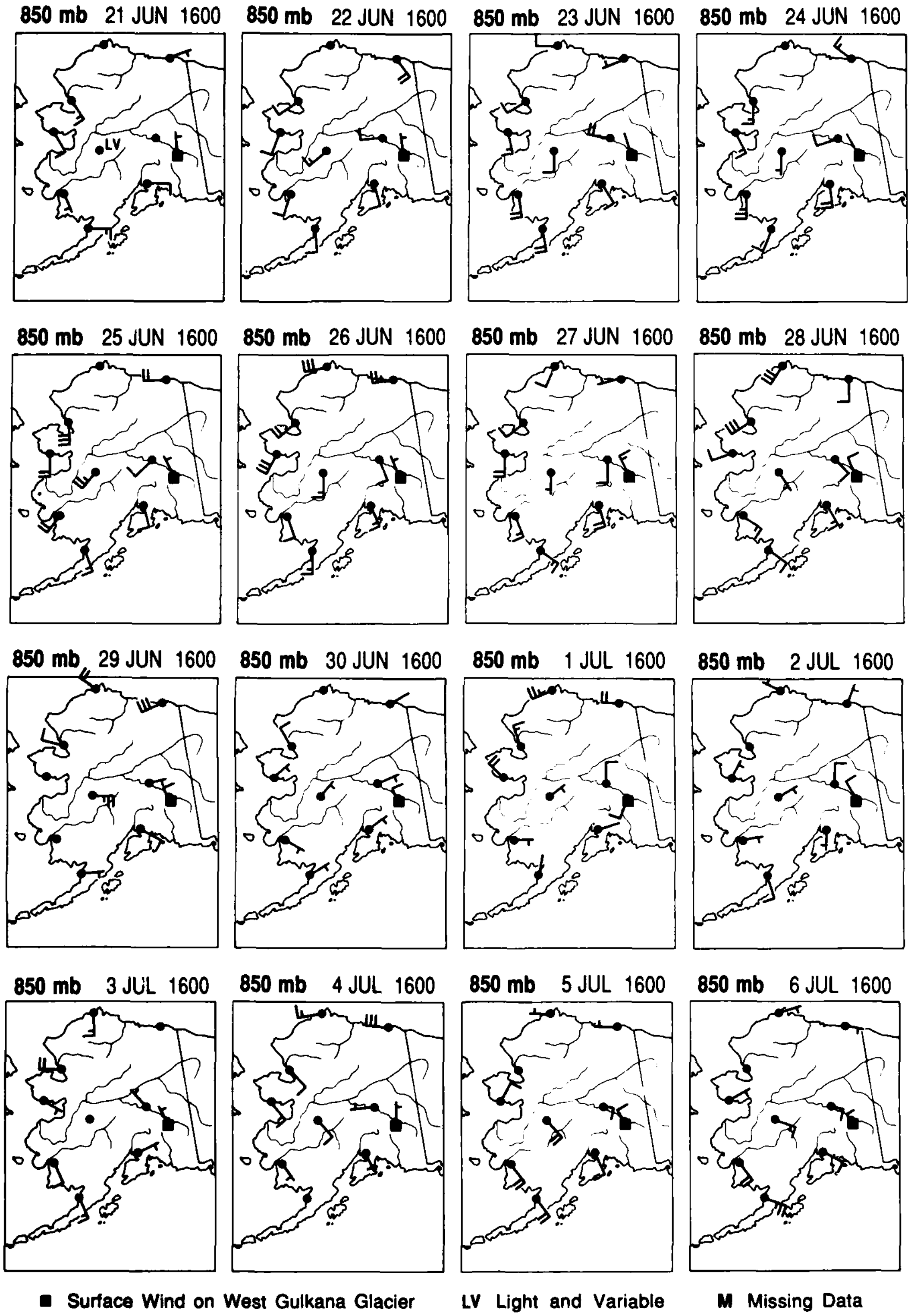
## CONCLUSIONS

Wind observations on West Gulkana conform to wind regimes detected for other glacier environments. Comparisons of upper level flow with glacier winds reveals important synoptic links to wind behavior on the glacier. Upper level flow in line with the downglacier direction often produced very turbulent winds on West Gulkana Glacier, exceeding 20 msec$^{-1}$. Weak pressure gradients aloft were commonly associated with a drainage wind regime with classical diurnal behavior observed on other glaciers.

Generally, wind directions aloft in an upglacier direction were associated with glacier wind velocities less than free air flow. Upper level flow in a downglacier direction assisted glacier wind velocities and caused glacier flow to exceed free air wind speeds at a comparable elevation to the glacier.

## REFERENCES

Streten, N. A. and Wendler, G., 1968. Some observations of Alaskan glacier winds in midsummer, Arctic, v. 2, 98-102.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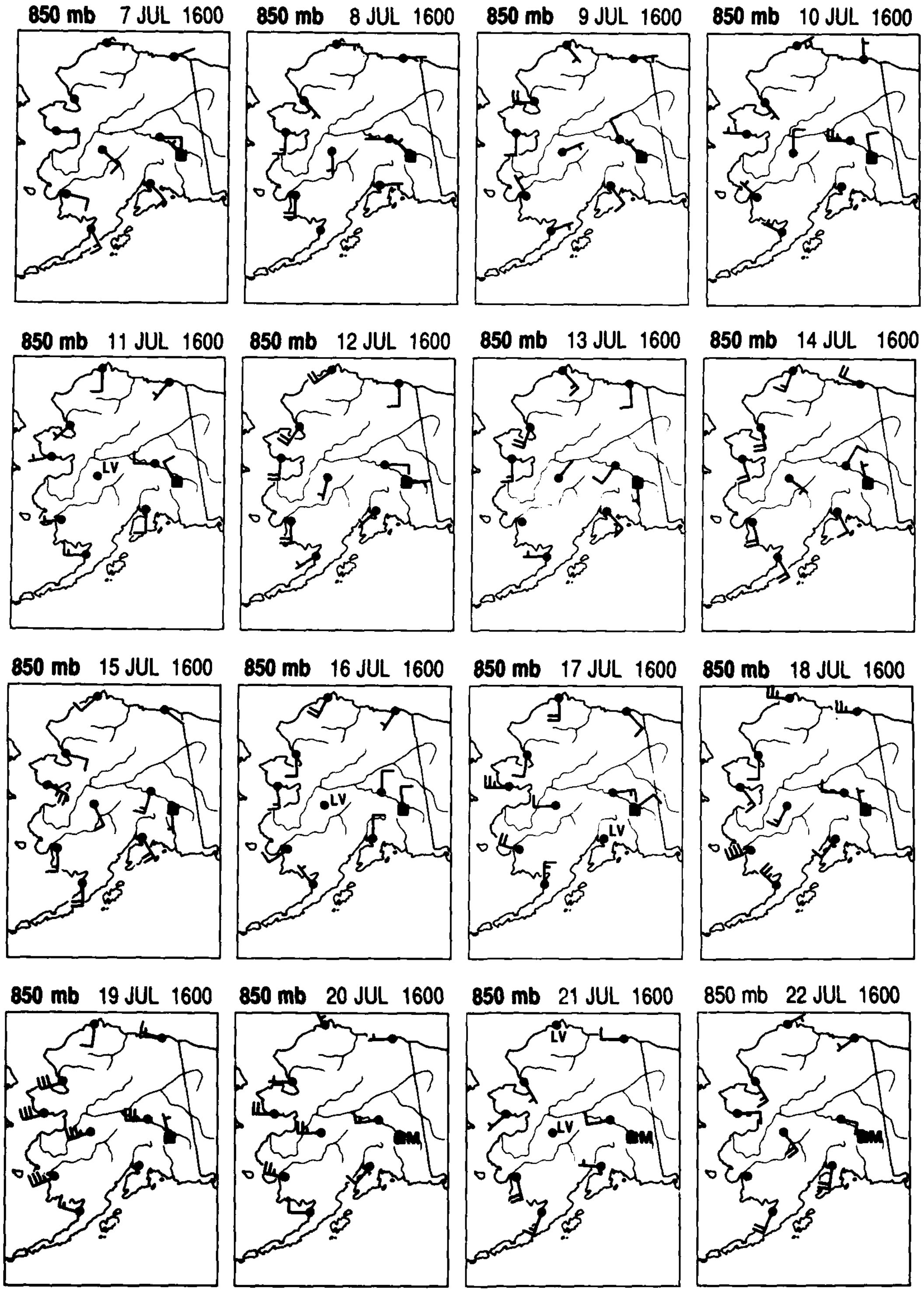
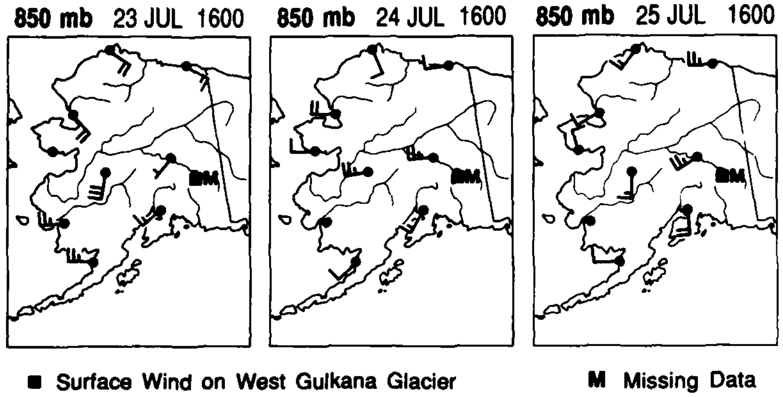
■ Surface Wind on West Gulkana Glacier
LV Light and Variable
M Missing Data

Figure 1.




■ Surface Wind on West Gulkana Glacier LV Light and Variable M Missing Data

Figure 1 (continued).

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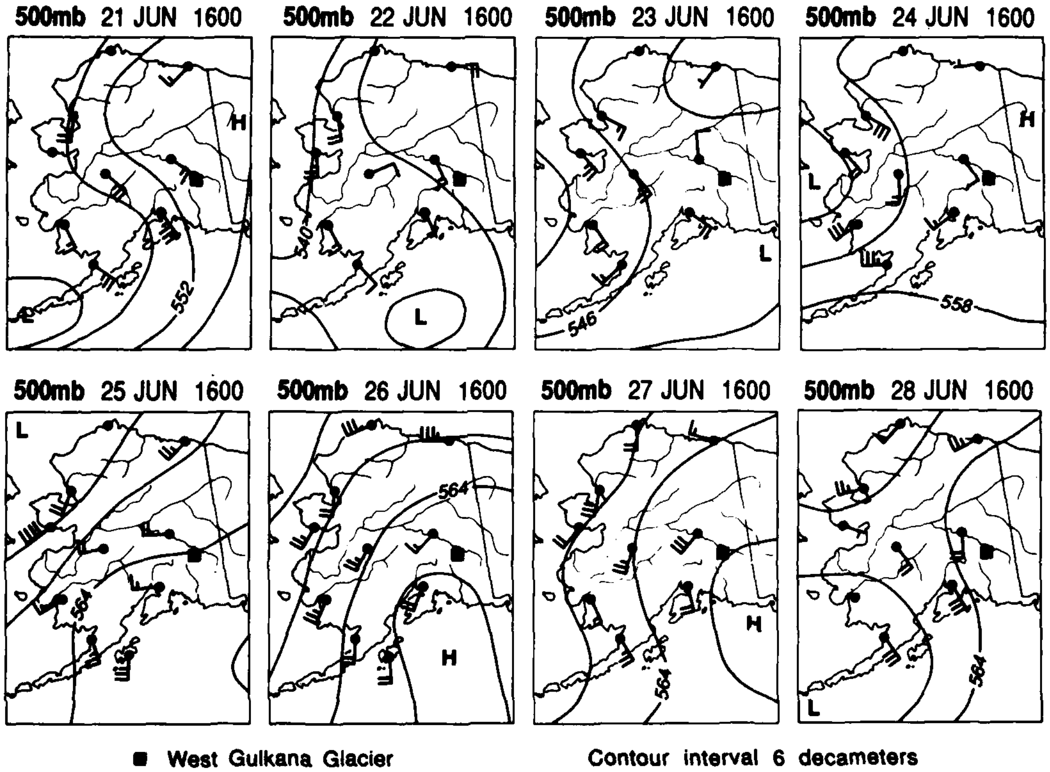
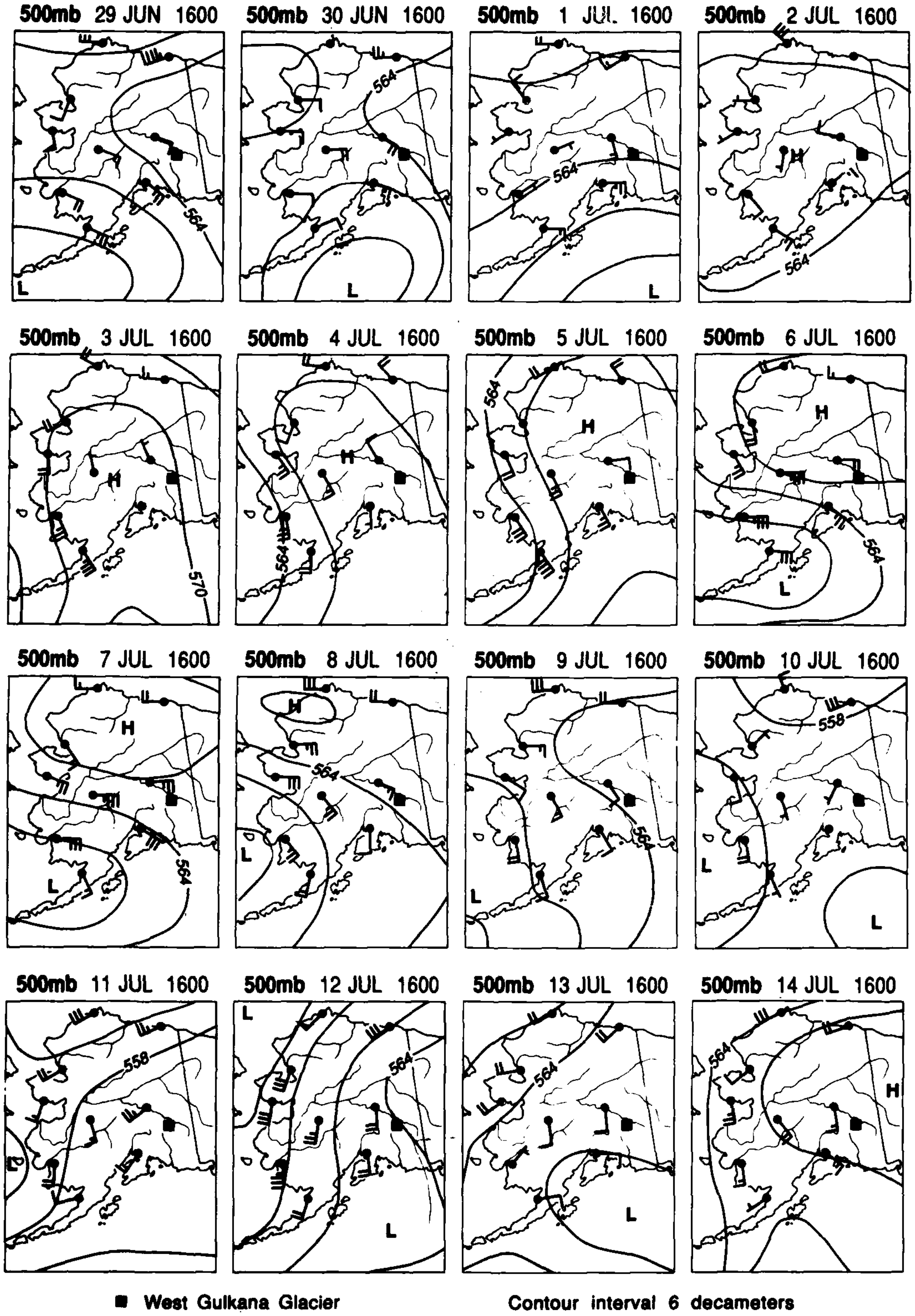



Figure 2.

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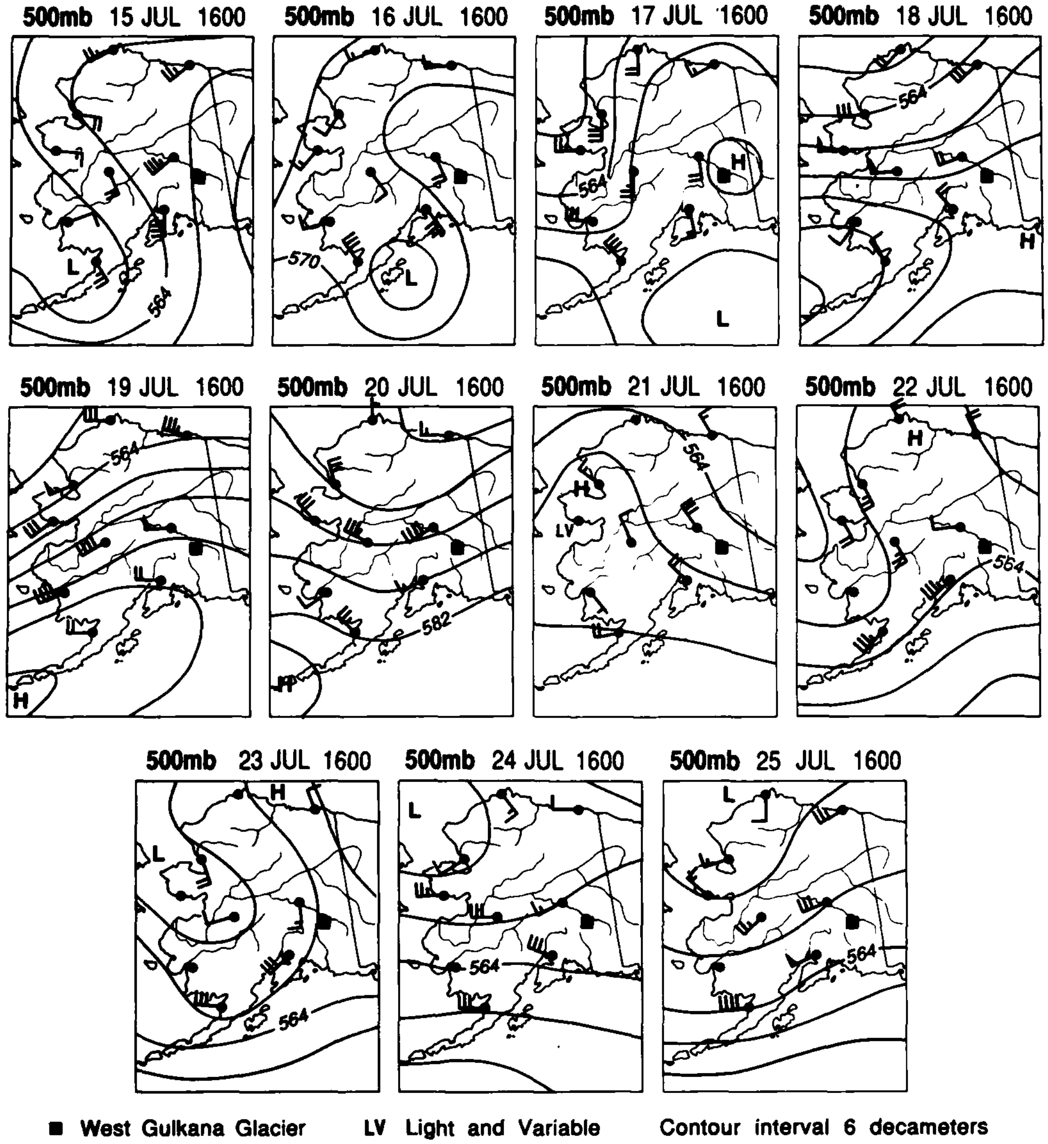


Figure 2 (continued).

# WINDS AT SUMMIT LAKE, ALASKA, DURING SUMMER, 1986

by

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## INTRODUCTION

Observations of wind speed and direction were made at Summit Lake Lodge on Summit Lake just south of Isabel Pass, Alaska ($63^{\circ}$ 20'N, $145^{\circ}$ 30' W; elevation, 978 m) for the period 21 June to 19 July, 1986. The meteorological observations made on the West Gulkana Glacier are supplemented by these wind data, which assist in understanding the local wind regime of the glacier in relation to both upper air patterns and wind along the southern flanks of the eastern Alaska Range.

Summit Lake Lodge is at the northeast corner of 3 km long Summit Lake, approximately 4.8 km south-southwest of the West Gulkana Glacier (see frontispiece). The lake is surrounded on the northwest, north, and northeast by mountains (ca. 2,800 m) of the east-central Alaska Range. Some 10 km to the north-northwest, the Delta River drains north through a gap in the ranges. Broad, undulating and sometimes level stretches of land tilt towards the Copper River lowlands to the south of Summit Lake. Some 100 km southeast, the Wrangell Mountains rise to elevations exceeding 4,800 m.

Local relief within 3 to 5 km of the lake varies with quadrant, but generally spans from 150 to 600 m above the lake. To the northeast, in the direction of the West Gulkana Glacier, elevations increase rapidly and the terrain is cut by many glacier-fed streams. Drainage to the south feeds the large Copper River system. Large glaciers within 20 km of the Summit Lake include the Gakona, Canwell, Black Rapids, Castner, and Gulkana systems.

## WIND OBSERVATION SYSTEM AND MEASUREMENTS

Continuous recordings of wind speed and direction were maintained at Summit Lake Lodges from 21 June - 19 July, 1986. The measurement system was positioned on the roof of the main lodge some 5 m above ground level. It consisted of an electronic Weather Measure Corp. Model 123-R, pressure sensitive paper strip chart recorder for wind velocity and direction. Time resolution on the recorder was 3 seconds. Due to frictional effects on the rotating drum which scrolls the paper, however, offset of time occurred. These offsets were minimized by time checks at the beginning, in the middle, and at the end of the recording period.

A method of correcting errors in time on the wind speed and direction charts was employed after all data were assembled at the end of the field season. A linear correction function was applied; it consisted initially of determining the total time error between known time checks on the charts. The assumption was that the time error detected on the charts appearing between two known time positions accumulated linearly. To correct all data for time, a phase shift of the traces was therefore necessary. The amount of shift per hour of trace was determined by dividing the total time error by the number of hours between the two accurately known points in time registered on the traces. A way to check the accuracy of this method was to look for known regionally windy periods from upper air data and glacier wind observations to check if Summit Lake data conformed in time to these periods. As a result, our method of data time correction by linear interpolation produced wind records that were not anomalous in relation to known windy periods elsewhere in the region.

Many characteristics of the wind data were extracted for analysis, such as peak half-hourly and hourly wind velocities and their associated wind directions, on-the-hour wind velocity and direction, and average hourly wind velocity and direction. This paper focuses on the hourly average wind speed and prevailing directions for 0100, 0400, 0700, 1000, 1300, 1600, 1900, and 2200 hours LST. Listings of wind data for the glacier, Summit Lake, and wind and cloud directions for 850 mb and 500 mb as observed from the glacier are provided for comparison of daytime wind conditions in the area. A frequency table was constructed based on the three-hourly periods listed above to show wind direction patterns on a diurnal and seasonal basis.

Tables 1 and 2 list hourly average winds around the three-hourly periods listed in these tables. The wind direction chart ran out on the 17th of July, but the wind speed chart was maintained through the 19th. Table 3 presents the diurnal wind direction frequency data for Summit Lake Lodge. Table 4 lists 1600 LST wind at the glacier meteorological site, Summit Lake Lodge, and free air 850 and 500 mb values interpolated from the Anchorage and Fairbanks 0000Z soundings. In addition, cloud tenths and direction are listed.

## WIND DIRECTION PATTERNS

Table 3 illustrates the frequency of wind directions for various times of the day at Summit Lake Lodge. The summer pattern shows a preference for a southerly component (0100-1300) and northeasterly to northwesterly component (1300-2200). Two contributing factors play a role in the development of this pattern. This location is transitional in summer to frequent troughs which promote a sequence of south-to-west-to-north flow as a low pressure migrates across the region, and to expansion of high pressure systems in eastern Alaska which tend to produce warm southerly flow (Brazel, Buckley, and Reynolds, this volume). However, there also is a tendency for a recognizable diurnal wind direction regime at Summit Lake. Early in the daytime, southerly flow is frequent. This may reflect upslope flow from the south and in line with the major axis of Summit Lake. A pronounced northerly component at night is evident in the frequency data.

TABLE 1

SUMMIT LAKE LODGE WIND VELOCITY, 1986
(meters per sec)

Time (LST)

| Date | 01 | 04 | 07 | 10 | 13 | 16 | 19 | 22 | Mean |
|---|---|---|---|---|---|---|---|---|---|
| 21 June | -- | -- | -- | 1.3 | 0.0 | 0.0 | 2.0 | 1.0 | 0.9 |
| 22 | 2.8 | 1.5 | 0.0 | 2.8 | 0.4 | 0.0 | 3.5 | 3.8 | 1.9 |
| 23 | 3.0 | 3.3 | 3.2 | 0.2 | 0.0 | 0.3 | 2.7 | 1.0 | 1.7 |
| 24 | 0.0 | 0.0 | 3.0 | 0.6 | 3.0 | 2.9 | 2.4 | 0.6 | 1.6 |
| 25 | 2.7 | 2.0 | 0.0 | 2.7 | 1.1 | 0.9 | 3.5 | 2.9 | 2.0 |
| 26 | 0.0 | 0.0 | 0.0 | 0.0 | 0.4 | 0.3 | 0.2 | 0.3 | 0.1 |
| 27 | 0.0 | 0.0 | 0.0 | 0.1 | 5.2 | 4.2 | 1.0 | 2.9 | 1.7 |
| 28 | 0.5 | 0.0 | 0.0 | 0.0 | 0.8 | 2.1 | 3.6 | 2.0 | 1.1 |
| 29 | 1.1 | 0.0 | 0.0 | 0.2 | 1.4 | 0.8 | 6.1 | 7.0 | 2.1 |
| 30 | 0.8 | 0.0 | 0.0 | 0.0 | 0.2 | 3.9 | 2.4 | 1.2 | 1.1 |
| 1 July | 7.2 | 3.2 | 0.0 | 9.3 | 10.9 | 4.9 | 10.3 | 11.3 | 7.1 |
| 2 | 6.5 | 10.3 | 5.1 | 3.6 | 1.3 | 0.7 | 6.8 | 2.3 | 4.6 |
| 3 | 0.0 | 0.0 | 0.0 | 0.4 | 3.1 | 5.0 | 4.6 | 0.0 | 1.6 |
| 4 | 0.0 | 0.0 | 0.0 | 0.3 | 1.1 | 0.4 | 3.6 | 2.6 | 1.0 |
| 5 | 0.9 | 0.3 | 0.0 | 1.8 | 3.4 | 0.8 | 4.7 | 0.0 | 1.5 |
| 6 | 1.4 | 0.0 | 1.0 | 4.5 | 1.3 | 2.7 | 3.6 | 5.6 | 2.5 |
| 7 | 0.1 | 0.0 | 0.0 | 1.0 | 3.4 | 7.4 | 11.6 | 3.2 | 3.3 |
| 8 | 2.8 | 4.3 | 1.1 | 1.6 | 2.5 | 0.0 | 0.6 | 0.4 | 1.7 |
| 9 | 0.3 | 0.3 | 0.0 | 0.0 | 2.2 | 8.9 | 0.0 | 7.7 | 2.4 |
| 10 | 0.0 | 0.0 | 3.7 | 12.6 | 14.9 | 10.1 | 6.8 | 7.0 | 6.9 |
| 11 | 0.0 | 0.0 | 0.0 | 0.0 | 0.6 | 8.8 | 9.9 | 9.3 | 3.6 |
| 12 | 0.3 | 0.2 | 0.3 | 5.6 | 7.2 | 2.7 | 0.0 | 8.0 | 3.0 |
| 13 | 2.2 | 0.0 | 0.0 | 1.0 | 11.6 | 7.4 | 0.0 | 2.0 | 3.0 |
| 14 | 1.6 | 1.0 | 0.0 | 1.9 | 1.8 | 1.1 | 2.8 | 0.0 | 1.3 |
| 15 | 1.6 | 0.0 | 4.1 | 4.0 | 10.1 | 6.4 | 9.1 | 1.0 | 4.5 |
| 16 | 0.9 | 0.0 | 0.8 | 1.4 | 0.3 | 4.5 | 7.5 | 12.3 | 3.5 |
| 17 | 12.9 | 8.9 | 11.3 | 7.0 | 6.3 | 7.2 | 5.9 | 4.3 | 8.0 |
| 18 | 8.3 | 14.0 | 13.9 | 14.5 | 9.7 | 5.9 | 1.8 | 1.9 | 8.8 |
| 19 | 0.0 | 0.0 | 2.0 | 6.3 | 1.9 | 2.6 | 0.5 | 0.6 | 1.7 |
| Mean | 2.1 | 1.8 | 1.8 | 2.9 | 3.7 | 3.6 | 4.1 | 3.5 | 2.9 |

## TABLE 2

### SUMMIT LAKE LODGE WIND DIRECTION, 1986
(in degrees azimuth)

| Date | 01 | 04 | 07 | 10 | 13 | 16 | 19 | 22 | Prev. |
|---|---|---|---|---|---|---|---|---|---|
| 21 June | -- | -- | -- | 220 | 165 | 225 | 45 | 180 | SW |
| 22 | 135 | 130 | 150 | 200 | 180 | 45 | 130 | 225 | SE |
| 23 | 165 | 140 | 130 | 150 | 230 | 125 | 120 | 145 | SE |
| 24 | 130 | 185 | 230 | 195 | 225 | 205 | 280 | 190 | SW |
| 25 | 180 | 185 | 205 | 260 | 150 | 270 | 305 | 45 | SW |
| 26 | 40 | 10 | 10 | 210 | 335 | 350 | 20 | 15 | NE |
| 27 | 25 | 25 | 185 | 205 | 200 | 185 | 180 | 45 | SW |
| 28 | 25 | 20 | 270 | 195 | 185 | 180 | 115 | 30 | SW |
| 29 | 35 | 180 | 315 | 100 | 100 | 260 | 20 | 50 | SW |
| 30 | 50 | 350 | 55 | 135 | 325 | 345 | 20 | 40 | NW |
| 1 July | 340 | 320 | 25 | 35 | 335 | 340 | 315 | 315 | NW |
| 2 | 175 | 200 | 180 | 40 | 35 | 180 | 180 | 5 | S |
| 3 | 175 | 350 | 320 | 25 | 40 | 350 | 20 | 145 | NW |
| 4 | 155 | 180 | 190 | 190 | 200 | 320 | 95 | 20 | SW |
| 5 | 10 | 190 | 200 | 185 | 90 | 20 | 150 | 10 | SW |
| 6 | 90 | 190 | 205 | 210 | 215 | 80 | 135 | 55 | SW |
| 7 | 40 | 350 | 195 | 200 | 145 | 185 | 220 | 150 | SW |
| 8 | 180 | 180 | 210 | 220 | 45 | 280 | 10 | 350 | SW |
| 9 | 45 | 190 | 330 | 90 | 315 | 350 | 0 | 330 | NW |
| 10 | 320 | 340 | 340 | 0 | 30 | 30 | 180 | 315 | NW |
| 11 | 300 | 315 | 0 | 345 | 35 | 325 | 320 | 0 | NW |
| 12 | 180 | 90 | 150 | 150 | 180 | 150 | 200 | 45 | SE |
| 13 | 40 | 55 | 315 | 315 | 315 | 320 | 100 | 220 | NW |
| 14 | 150 | 170 | 180 | 200 | 130 | 55 | 20 | 90 | SE |
| 15 | 235 | 40 | 350 | 315 | 0 | 15 | 330 | 330 | NW |
| 16 | 350 | 45 | 0 | 315 | 320 | 320 | 330 | 340 | NW |
| 17 | 0 | 15 | 10 | 210 | 195 | 105 | 135 | 115 | SE |

Prev. = prevailing direction; that is, the direction occurring for half or more of the time.

This flow is aligned with the elongated axis of the lake and on clear nights may emanate from drainage flow derived from the uplands north of the lake.

A perusal of Table 4 reveals that afternoon flow at Summit Lake (1600 LST) usually conforms to the interpolated wind flow direction of the Fairbanks/Anchorage sounding data at the 850 mb level. On sixteen of the twenty-six days of the sample, this was the case. Of the remaining ten days, on only two of them did the

TABLE 3

**SUMMIT LAKE LODGE WIND DIRECTION FREQUENCY BY TIME OF DAY***
(percent frequency)

| | Direction | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Time | N | NE | E | SE | S | SW | W | NW |
| 0100 | 14.3 | 28.6 | 3.6 | 14.3 | 21.4 | 3.6 | 0 | 7.1 |
| 0400 | 25.0 | 14.3 | 3.6 | 7.1 | 35.7 | 0 | 0 | 7.1 |
| 0700 | 21.4 | 7.1 | 0 | 10.7 | 21.4 | 14.3 | 3.6 | 14.3 |
| 1000 | 6.9 | 10.3 | 6.9 | 10.3 | 21.4 | 20.7 | 3.4 | 10.3 |
| 1300 | 3.4 | 17.2 | 6.9 | 10.3 | 24.1 | 10.3 | 0 | 20.7 |
| 1600 | 24.1 | 10.3 | 6.9 | 6.9 | 13.8 | 6.9 | 10.3 | 13.8 |
| 1900 | 24.1 | 3.4 | 13.8 | 13.8 | 13.8 | 3.4 | 3.4 | 17.2 |
| 2200 | 24.1 | 24.1 | 6.9 | 10.3 | 6.9 | 6.9 | 0 | 13.8 |
| Mean | 17.9 | 14.4 | 6.1 | 10.5 | 20.2 | 8.3 | 2.6 | 13.0 |

* For the period 21 June to 17 July, 1986.

afternoon flow depart from the 850 mb direction by more than one quadrant of azimuth direction (i.e., by $90^{o}$); however, on only eleven of the twenty-six days were wind directions at 1600 LST similar at Summit Lake and on the West Gulkana glacier. On five of these eleven days, West Gulkana and Summit Lake Lodge wind directions were similar to each other and to the direction at the 850 mb level. On the other six days--when West Gulkana and Summit Lake Lodge 1600 LST directions were similar--the 850 mb direction of flow was in an opposing direction to these two locations. All of these six days occurred early in the sample period when most of the mountainous terrain was still snow-covered by an early summer snowstorm.

Similar downslope wind flow directions at Summit Lake and West Gulkana during this time (in opposition to weak southerly flow at 850 and 500 mb) may relate to induced downglacier

TABLE 4

**WIND VELOCITY AND DIRECTION FOR 1600 LST AT WEST GULKANA GLACIER, SUMMIT LAKE LODGE, AND FREE AIR* FOR SUMMER SEASON, 1986**

| | Glacier | | Summit | | 850 mb | | 500 mb | | Glacier | |
|---|---|---|---|---|---|---|---|---|---|---|
| Date | v | d | v | d | v | d | v | d | Cloud | cd |
| 21 June | 1.6 | N | 0.0 | SW | 5.0 | SSE | 5.8 | SE | 10 | E |
| 22 | 1.9 | N | 0.0 | NE | 5.0 | SW | 5.0 | SE | 10 | W |
| 23 | 0.8 | NNW | 0.3 | SSW | 8.9 | WSW | 7.7 | ENE | 10 | - |
| 24 | 0.8 | NNW | 2.9 | W | 7.7 | SW | 6.5 | S | 8 | W |
| 25 | 1.3 | NNW | 0.9 | N | 5.1 | SSW | 9.1 | W | 10 | W |
| 26 | 1.8 | NNW | 0.3 | S | 6.5 | SSE | 9.1 | SSW | 2 | SW |
| 27 | 3.8 | NNW | 4.2 | S | 6.4 | S | 12.9 | SSW | 1 | W |
| 28 | 3.9 | NNW | 2.1 | E | 6.5 | SE | 11.6 | SSE | 4 | SE |
| 29 | 4.6 | NNW | 0.8 | N | 3.8 | ESE | 8.9 | SE | 1 | S |
| 30 | 4.1 | NNW | 3.9 | N | 3.8 | ENE | 9.1 | SE | 1 | E |
| 1 July | 3.9 | NW | 4.9 | S | 2.9 | NE | 10.3 | SE | 5 | SE |
| 2 | 6.2 | NNW | 0.7 | N | 5.1 | E | 6.5 | NE | 3 | SE |
| 3 | 2.8 | NNW | 5.0 | NW | 2.5 | NE | 1.2 | N | 7 | E |
| 4 | 2.6 | N | 0.4 | NE | 5.1 | NW | 3.8 | NW | 7 | NW |
| 5 | 4.6 | NNW | 0.8 | E | 3.8 | SE | 8.9 | SE | 5 | S |
| 6 | 4.7 | NNW | 2.7 | S | 5.1 | SE | 11.5 | ESE | 3 | SE |
| 7 | 3.2 | NW | 7.4 | W | 3.8 | SE | 14.1 | ESE | 9 | E |
| 8 | 1.5 | NW | 0.0 | N | 2.5 | W | 6.5 | SE | 10 | N |
| 9 | 2.8 | NW | 8.9 | NE | 5.1 | NE | 5.1 | SSE | 6 | S |
| 10 | 6.1 | N | 10.1 | NW | 12.7 | W | 2.5 | S | 2 | SE |
| 11 | 4.7 | NNW | 8.8 | SE | 5.1 | SW | 10.3 | SW | 10 | N |
| 12 | 2.8 | E | 2.7 | NW | 2.5 | E | 10.3 | S | 10 | SE |
| 13 | 2.3 | S | 7.4 | NE | 5.1 | S | 5.1 | SE | 10 | NW |
| 14 | 0.6 | NNW | 1.1 | NNE | 2.5 | NE | 7.8 | S | 8 | S |
| 15 | 3.0 | S | 6.4 | NW | 9.1 | SSE | 16.8 | SW | 9 | S |
| 16 | 4.5 | N | 4.5 | SE | 5.1 | N | 12.9 | SSE | 5 | SE |
| 17 | 3.9 | NE | 7.2 | -- | 3.9 | E | 9.1 | S | 3 | SE |
| 18 | 3.7 | NNW | 5.9 | -- | 5.1 | SW | 10.3 | W | 10 | W |
| Mean | 3.7 | | 3.6 | | 5.2 | | 8.5 | | 6.4 | |

* Interpolated winds from Anchorage/Fairbanks soundings at 0000Z
v = wind velocity in $msec^{-1}$
d = wind direction
cloud = tenths of cloud cover over glacier site
cd = direction from which clouds are moving

drainage flow over the snow covered terrain and from uplands towards the lake while a high pressure system hovered over the region. With but few exceptions, cloud directions observed at the glacier meteorological station agreed well with the 850 and

500 mb flow directions.

## WIND VELOCITY COMPARISONS

Hourly average wind velocities registered at West Gulkana at 1600 LST ranged from 0.8 to 6.2 $msec^{-1}$; at Summit Lake Lodge, from 0.0 to 10.1 $msec^{-1}$; at the 850 mb level, 2.5 to 12.7 $msec^{-1}$, and at the 500 mb level, 1.2 to 16.8 $msec^{-1}$. Seasonal averages were 3.7, 3.6, 5.2, and 8.5 $msec^{-1}$, respectively. Therefore, West Gulkana wind velocities average almost the same as those recorded at Summit Lake Lodge, even though the West Gulkana glacier is at considerably higher elevation and in a channeled valley environment. The recorder at Summit Lake was 5 m above ground, as opposed to 1.5 m on the glacier. Also, the smooth lake surface and large fetch effects around the lodge location could account for the comparability with West Gulkana wind flow strength. Glacier winds at 1600 LST average much less than the winds experienced at the corresponding free air 850 mb level, illustrating the mountain barrier frictional effect on wind in this glacier environment. *However, during periods when upper* level flow aligns with surface flow and the atmosphere is unstable, winds on the glacier were greatly accelerated (Brazel, Buckley, and Reynolds, this volume).

## CONCLUSIONS

Wind observations were maintained at Summit Lake Lodge during the field season of 1986 (21 June to 19 July). These data proved to be useful for analysis of regional wind flow patterns and in understanding further characteristics of the wind regime on the West Gulkana glacier. The glacier wind direction pattern differs substantially from locations along the flanks of the mountain range. The comparison of Summit Lake, free air flow and glacier flow indicates that there is a consistent downglacier wind in comparison to free air flow and surface flow along the southern periphery of the Alaskan range. Surges in wind on the glacier are promoted by synoptic conditions yielding wind flow directions in alignment with the down-glacier direction.

## COMPARISON OF 0000Z UPPER AIR TEMPERATURES WITH 1600 LST WEST GULKANA GLACIER AIR TEMPERATURES

by

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### INTRODUCTION

Air temperature observations on West Gulkana Glacier were taken as part of standard measurements at the main glacier meteorological station during the summer, 1986 (see Brazel, Marcus, and Moore, this volume). These data were taken at synoptic hours primarily during the daytime. This short paper summarizes temperature data for 0000Z (1600 Alaskan Time) in order that upper air temperatures can be compared to surface temperatures experienced on the glacier. A correlation between upper air values and glacier surface temperatures is useful for developing ablation models and in understanding the links between air flow over the Alaskan Range and conditions on the glacier.

Table 1 gives a data summary of temperatures (and cloud cover) for the period June 21 to July 19, 1986. The table lists date, cloud cover, glacier air temperature, 850 mb temperature, 500 mb temperature, and glacier minus 850 mb temperature. The cloud cover was that recorded at the meteorological site on the glacier. The 850 and 500 mb temperatures were extracted from the NOAA Northern Hemisphere analysis maps obtained from National Climatic Data Center (see Brazel, Buckley, and Reynolds, this volume) and represent the average value of the Anchorage and Fairbanks temperatures at respective levels in the atmosphere. The 850 mb level in the atmosphere is close to the elevation of the meteorological site on the glacier (1495m). Several graphs were constructed to indicate the comparison between free air temperatures and glacier surface temperatures (see Figures 1-3) and Table 2 is useful for statistical comparison of the glacier with the free air values.

## RESULTS OF TEMPERATURE ANALYSIS

Table 1 indicates that the glacier temperatures at 1600 LST are within 2 to 3 $^{o}C$ of the 850 mb values most of the 29 days of the sample. On thirteen of those days temperatures over the ice were cooler than the 850 mb level, and on 16 days they were warmer.

The time trend of the 1600 LST air temperatures over the 29 days on the glacier and at 850 and 500 mb is shown in Figure 1. Note distinct warming at all levels in the first half of the period, interrupted by a rather abrupt cooling period, and again followed at the end of the period by warming. The first third of the record is relatively cloud-free, while the last two thirds is quite cloudy (Table 1 and Figure 1).

Table 2 is a correlation matrix relating glacier temperatures, 850 mb temperatures individually for Anchorage and Fairbanks, and the average of the two stations at 850 and 500 mb levels, in addition to cloud cover observed at the glacier site. Correlations are moderately high (significant at the 0.05 level) for cloudiness versus temperatures on the glacier ($r = -0.578$) and for 850 mb interpolated temperatures (mean of Anchorage and Fairbanks values) versus glacier surface temperatures ($r = 0.689$). Figures 2 and 3 show the scattergram and least-squares, best-fit line in these individual relationships. Since these two factors appear to have the highest individual correlations with the glacier surface air temperature at 1600 LST, a stepwise multiple correlation and regression analysis was performed with the glacier air temperature as dependent variable and cloudiness and interpolated 850 mb free air temperatures as the independent variables. Let $T_{glac}$ symbolize the air temperature at 1600 LST on the glacier, Cl equal cloud cover in tenths, and $T_{850}$ equal the interpolated temperature at 850 mb over the glacier. The following resulted from the multiple correlation and regression

## TABLE 1

### GLACIER TEMPERATURES, CLOUD COVER, AND UPPER AIR TEMPERATURES 1600 LOCAL TIME

| Date | Glacier Temp (° C) | 850 Temp (° C) | 500 Temp (° C) | ΔT Glac-850 | Cloud Cover (tenths) |
|---|---|---|---|---|---|
| 21 June | 4.4 | 5.0 | -20.5 | -0.6 | 10 |
| 22 | 5.6 | 4.5 | -23.5 | 1.1 | 10 |
| 23 | 4.4 | 1.5 | -24.0 | 2.9 | 10 |
| 24 | 3.0 | 2.0 | -24.0 | 1.0 | 8 |
| 25 | 4.0 | 2.0 | -21.5 | 2.0 | 10 |
| 26 | 8.0 | 5.5 | -19.0 | 2.5 | 2 |
| 27 | 9.0 | 9.5 | -20.0 | -0.5 | 1 |
| 28 | 12.0 | 9.5 | -21.0 | 2.5 | 4 |
| 29 | 9.2 | 9.5 | -20.5 | -0.3 | 4 |
| 30 | 11.5 | 11.0 | -19.0 | 0.5 | 1 |
| 1 July | 13.0 | 11.0 | -17.0 | 2.0 | 5 |
| 2 | 10.5 | 10.5 | -15.0 | 0.0 | 3 |
| 3 | 9.2 | 11.5 | -15.5 | -2.3 | 7 |
| 4 | 11.8 | 12.0 | -15.5 | -0.2 | 7 |
| 5 | 9.5 | 12.5 | -14.5 | -3.0 | 5 |
| 6 | 8.6 | 12.5 | -15.5 | -3.9 | 3 |
| 7 | 6.2 | 9.5 | -18.0 | -3.3 | 9 |
| 8 | 6.0 | 6.0 | -18.0 | 0.0 | 9 |
| 9 | 6.2 | 7.0 | -18.0 | -0.8 | 6 |
| 10 | 6.5 | 8.0 | -18.0 | -1.5 | 2 |
| 11 | 8.2 | 9.0 | -19.0 | -0.8 | 9 |
| 12 | 11.2 | 7.5 | -18.0 | 3.7 | 10 |
| 13 | 3.1 | 5.0 | -20.5 | -1.9 | 10 |
| 14 | 9.0 | 6.0 | -18.5 | 3.0 | 8 |
| 15 | 7.8 | 6.0 | -17.0 | 1.8 | 9 |
| 16 | 9.4 | 6.0 | -17.0 | 3.4 | 5 |
| 17 | 14.2 | 12.5 | -16.0 | 1.7 | 4 |
| 18 | 6.1 | 5.0 | -15.5 | 1.1 | 10 |
| 19 | 3.3 | 11.0 | -13.5 | -7.7 | 10 |

analysis:

$$T_{glac} = 5.98 - 0.291\ Cl + 0.495\ T_{850},$$

with a multiple correlation r squared of 0.5382 (r = 0.7336) and standard error of the estimate of 2.18 °C. The r-squared value is significant at the 95 % confidence level. A plot of the residuals from regression are shown in Figure 4.

Generally the residual plot follows the absolute temperature trend through the season, with two periods of positive residuals (corresponding to the two warm spells) and a negative residual

**TABLE 2**

**CORRELATION MATRIX OF SURFACE AND UPPER AIR TEMPERATURES AND CLOUD COVER**

| | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| 1 | | | | | | |
| 2 | 0.497 | | | | | |
| 3 | -0.422 | -0.487 | | | | |
| 4 | 0.545 | 0.640 | -0.578 | | | |
| 5 | 0.839 | 0.889 | -0.528 | 0.689 | | |
| 6 | 0.690 | 0.550 | -0.201 | 0.405 | 0.709 | 1.000 |

1 = Anchorage 850 mb upper air temperature at 1600 LST
2 = Fairbanks 850 mb upper air temperature at 1600 LST
3 = Cloud cover in tenths recorded on the glacier
4 = Glacier air temperature at the main mete. site
5 = Interpolated 850 mb air temperature over West Gulkana
6 = Interpolated 500 mb air temperature over West Gulkana.

period corresponding to the mid-season cool spell. The large negative residuals of mid-season (e.g., 6 and 10 July) occur on days with relatively clear skies, warm southerly flow aloft, but downglacier cold winds. Reasons for the large positive residuals are not as clear, but appear to relate to troughing aloft (upper level cooling, particularly indicated by the 500 mb level) with not much pronounced cooling effect on those days over the glacier. Further detailed analysis is warranted to evaluate free air correlations with glacier temperatures during these conditions.

## CONCLUSIONS

Upper air temperatures at 850 mb and an estimate of cloudiness over West Gulkana Glacier can produce statistically significant estimates of afternoon air temperatures over mid-glacier in summer. Standard errors of estimates using a multiple regression equation are in the range of 2 to 3 $^{o}$C. Anchorage and Fairbanks soundings were employed to interpolate temperatures at 850 mb and 500 mb over the Central Alaskan Range in the vicinity of the West Gulkana Glacier. Soundings from Fort Greely to the north of the Alaskan Range and closer to the glacier than Fairbanks should be analyzed further. Portable in-field sampling may provide further explanations for significant deviations indicated by the residuals from regression in this study, which only used Anchorage and Fairbanks soundings for interpolations for the glacier surface.

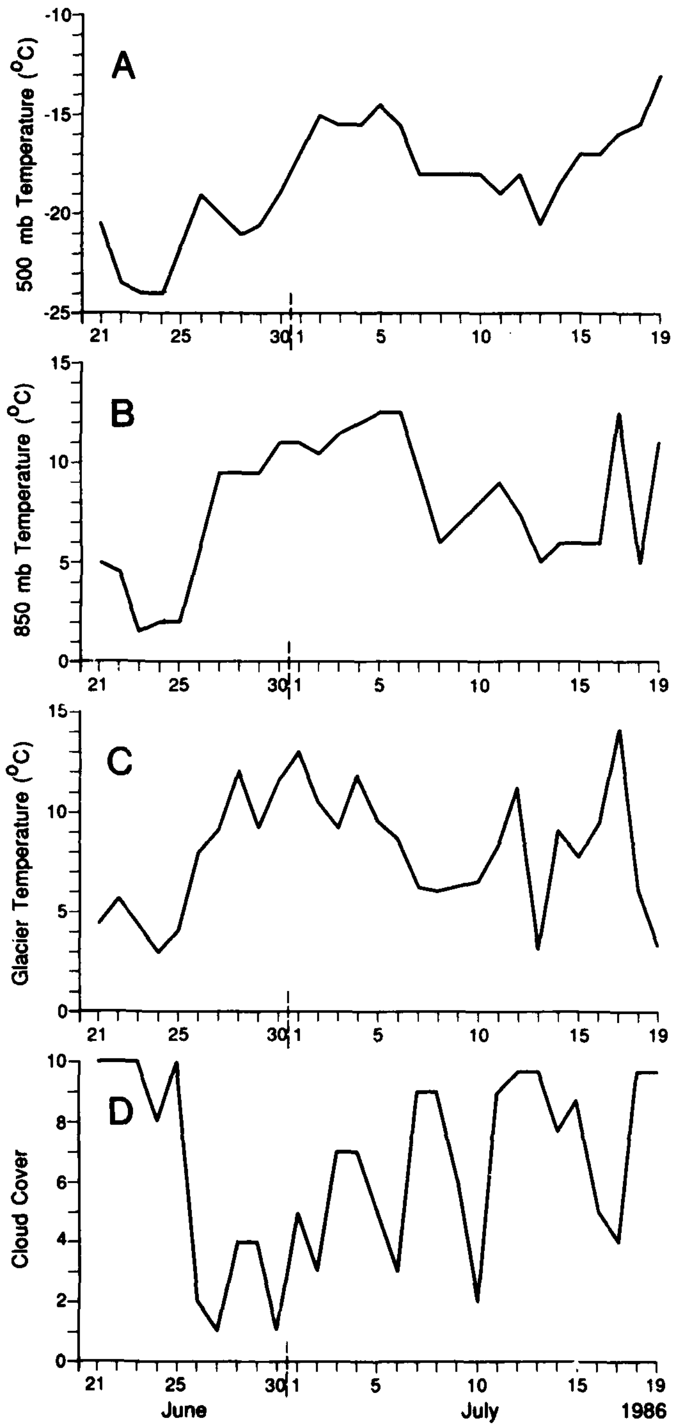


Figure 1. (a) Plot of 1600 LST 500 mb free air temperature; (b) plot of 1600 LST 850 mb free air temperature; (c) plot of 1600 LST near-surface glacier air temperature; (d) plot of 1600 LST cloud cover (10ths) observed at meteorological site, West Gulkana Glacier.

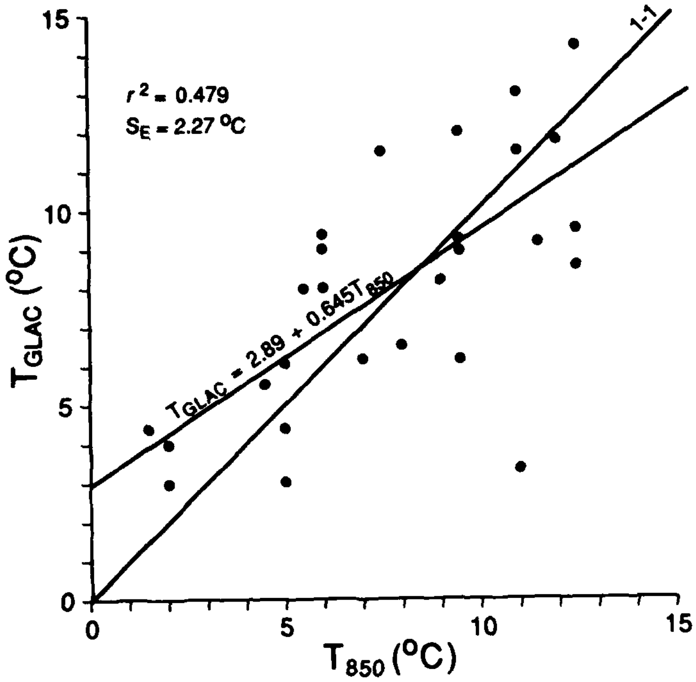


Figure 2. Plot of $T_{glac}$ versus $T_{850}$ for West Gulkana Glacier. $T_{850}$ is interpolated

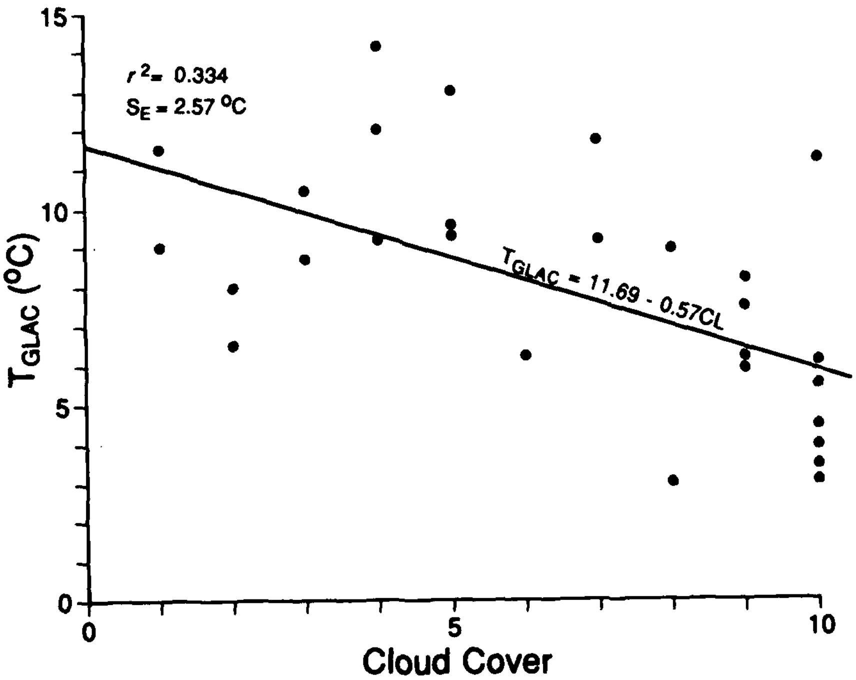


Figure 3. Plot of $T_{glac}$ versus cloud cover for 1600 LST.

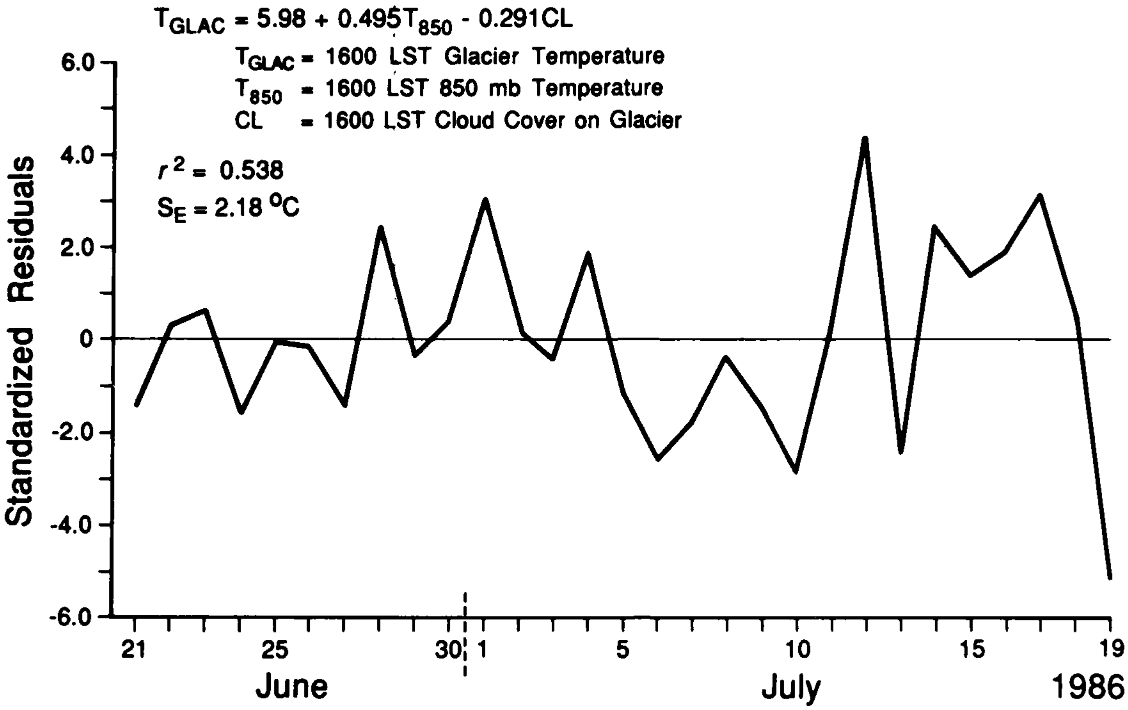


Figure 4. Time trend of standardized residuals from multiple regression of $T_{glac}$ versus $T_{850}$ and cloud cover for 1600 LST.

## SUMMER FIELD SEASON WEATHER OBSERVATIONS WEST GULKANA GLACIER AND ENVIRONS: 1986, 1987

by

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Meteorological observations were recorded on the West Gulkana Glacier, Alaska, and environs during the 1986 and 1987 field research seasons. These observations were not a scientific objective unto themselves; rather, they provide reference and base data for investigators working on the Project's various glaciological and climatological programs.

### 1986 OBSERVATIONS

In 1986, standard weather observations were recorded at the main glacier campsite on a 3-hour schedule from 0900 h to 1900 h, Alaska Daylight Time (station data and locations are shown in Table 1 and Figure 1 respectively). The period of record was 21 June through 21 July. Hourly observations were taken during three micrometeorological sampling periods: 1000 h, 27 June - 1600 h, 29 June; 1900 h, 5 July - 2000 h, 7 July; and 1200 h, 17 July - 1200 h, 19 July. The following were recorded: maximum and minimum temperature; wet and dry bulb temperature; amount and type of precipitation; wind speed and direction; visibility; cloud type, height, cover, and direction of movement; and snow/ice accumulation/ablation. The latter were measured at a 5-stake farm 50 m west-northwest of the weather shelter.

Drum hygrothermographs were operated at the glacier camp, on the east lateral moraine slopes, and on moraine c. 50 m from the glacier terminus. Shortwave radiation was continuously recorded on Belfort Actinographs at the main camp and terminus sites. Also, recording anemometers were installed at Summit Lake Lodge and on the east lateral moraine. Periods of record for the above stations are given in Table 1.

TABLE 1

WEATHER OBSERVATION SITES,
WEST GULKANA GLACIER PROJECT: 1986, 1987

| STATION | ELEVATION (m) | LATITUDE/ LONGITUDE | TYPE SURFACE | PERIOD OF RECORD | TYPE OF OBSERVATION |
|---|---|---|---|---|---|
| Glacier Camp | 1495 | 63°16'N 145°28'W | Snow, Ice | 06/22 - 07/19/86 | 1st Order |
| (hygrothermograph and actinograph) ..... | | | | 06/20- 07/21/86 | Temp., RH, Insolation |
| Tundra Camp | 1265 | 63°14'N 145°27'W | Tundra | 06/28 - 07/26/87 | 1st Order |
| (hygrothermograph and actinograph) .... | | | | as above | |
| Terminus | 1325 | 63°16'N 145°28'W | Moraine | 06/23 - 07/23/86 06/28 - 07/26/87 | Temp., RH, Insolation |
| East Lateral Moraine | 1550 | 63°16'N 145°28'W | Icecore Moraine | 07/02 - 07/21/86 | Temp., RH, Insolation |
| Summit Lake Lodge | 982 | 63°20'N 145°30'W | Gravel | 06/21 - 07/19/86 | Wind |

## 1987 OBSERVATIONS

Weather observations during the 1987 field season was not as elaborate, given fewer personnel and a greater emphasis on glaciological aspects of the research. For logistical reasons, the main camp (and its weather station) was moved off the glacier and onto a tundra-matted bench -- c. 1500 m south of the West Gulkana terminus and c. 60 m above the outwash stream (Figure 1).

The period of record was 28 June - 26 July. Elements observed were the same as for 1986 at the Glacier Camp, however, observations were made only at the beginning and end of the work day. Field workers were out of the camp at most times. Hygrothermograph and actinograph observations provide useful information for those times. Micrometeorological runs were made during the periods 1200 h, 2 July to 1800 h, 3 July, 0800 h, 5 July to 0900 h. 6 July, and 0800-1800 h, 11 July. More frequent regular weather observations were taken at these times.

As in 1986, a hygrothermograph and an actinograph were maintained at the Terminus site. Micrometeorological observations were also conducted from 1500 h, 21 July through 1100 h, 23 July at a site about 600 m directly upglacier from the 1986 Glacier Camp's position. Although specific climatological studies are addressed elsewhere in this volume, the following tables summarize general 1986 and 1987 field season weather.

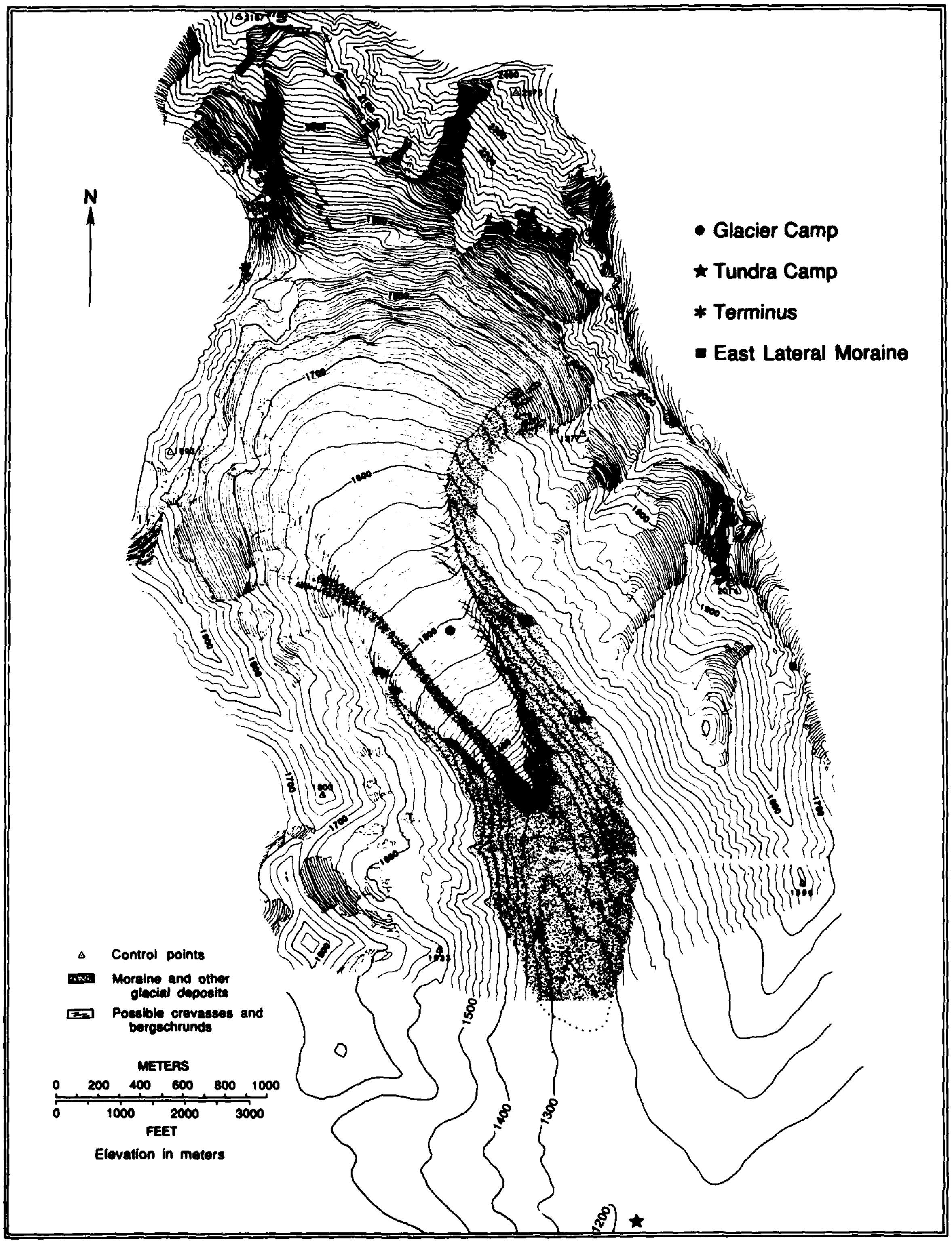

N
● Glacier Camp
★ Tundra Camp
✱ Terminus
■ East Lateral Moraine
Control points
Moraine and other glacial deposits
Possible crevasses and bergschrunds
METERS
0 200 400 600 800 1000
0 1000 2000 3000
FEET
Elevation in meters
1500
1400
1300
1200

Figure 1.

TABLE 2

DAILY MAXIMUM TEMPERATURE (Degrees C)
GLACIER CAMP
1986 FIELD SEASON

| Mth/Day | 0100 | 0400 | 0700 | 1000 | 1300 | 1600 | 1900 | 2200 |
|---|---|---|---|---|---|---|---|---|
| June 20 | | | | | | | | |
| 21 | | | | | | | | |
| 22 | | | | | | | | |
| 23 | | | 9.4 | | | | | |
| 24 | | | 11.7 | | | | | |
| 25 | | | 11.1 | | | | | |
| 26 | | | 9.4 | | | | | |
| 27 | | | | | | | | |
| 28 | | | 13.9 | | | | | |
| 29 | | | 15.0 | | | | | |
| 30 | | | 15.0 | | | | | |
| July 1 | | | 15.0 | | | | | |
| 2 | | | 14.4 | | | | | |
| 3 | | | 16.1 | | | | | |
| 4 | | | 13.9 | | | | | |
| 5 | | | 13.3 | | | | | |
| 6 | | | 18.3 | | | | | |
| 7 | | | 16.1 | | | | | |
| 8 | | | 13.3 | | | | | |
| 9 | | | 8.9 | | | | | |
| 10 | | | 11.1 | | | | | |
| 11 | | | 10.6 | | | | | |
| 12 | | | 13.9 | | | | | |
| 13 | | | 12.8 | | | | | |
| 14 | | | 5.6 | | | | | |
| 15 | | | 10.6 | | | | | |
| 16 | | | 10.3 | | | | | |
| 17 | | | 12.8 | | | | | |
| 18 | | | 16.7 | | | | | |
| July 19 | | | 11.7 | | | | | |

TABLE 3

DAILY MINIMUM TEMPERATURE (Degrees C)
GLACIER CAMP
1986 FIELD SEASON

| Mth/Day | 0100 | 0400 | 0700 | 1000 | 1300 | 1600 | 1900 | 2200 |
|---|---|---|---|---|---|---|---|---|
| June 20 | | | | | | | | |
| 21 | | | | | | | | |
| 22 | | | | | | | | |
| 23 | | | -1.1 | | | | | |
| 24 | | | -1.1 | | | | | |
| 25 | | | -0.6 | | | | | |
| 26 | | | -1.1 | | | | | |
| 27 | | | | | | | | |
| 28 | | | 4.4 | | | | | |
| 29 | | | 3.9 | | | | | |
| 30 | | | 3.3 | | | | | |
| July 1 | | | 4.4 | | | | | |
| 2 | | | 8.3 | | | | | |
| 3 | | | 4.4 | | | | | |
| 4 | | | 5.5 | | | | | |
| 5 | | | 6.1 | | | | | |
| 6 | | | 5.6 | | | | | |
| 7 | | | 3.9 | | | | | |
| 8 | | | 2.8 | | | | | |
| 9 | | | 2.2 | | | | | |
| 10 | | | 4.4 | | | | | |
| 11 | | | 4.4 | | | | | |
| 12 | | | 5.0 | | | | | |
| 13 | | | 2.2 | | | | | |
| 14 | | | 1.7 | | | | | |
| 15 | | | 2.2 | | | | | |
| 16 | | | 3.9 | | | | | |
| 17 | | | 6.7 | | | | | |
| 18 | | | 5.6 | | | | | |
| July 19 | | | 4.4 | | | | | |

TABLE 4

DRY BULB TEMPERATURE (Degrees C)
GLACIER CAMP
1986 FIELD SEASON

| Mth/Day | 0100 | 0400 | 0700 | 1000 | 1300 | 1600 | 1900 | 2200 | Daytime Mean |
|---|---|---|---|---|---|---|---|---|---|
| June 20 | | | | | | | 3.3 | | |
| 21 | | | 2.2 | 6.1 | 3.9 | 4.4 | 3.3 | | 4.0 |
| 22 | | | 2.8 | 2.8 | 6.7 | 5.6 | 2.8 | | 4.1 |
| 23 | | | -0.6 | 1.7 | 2.2 | 4.4 | 2.2 | | 2.0 |
| 24 | | | 0.6 | 2.8 | 5.0 | 3.0 | 1.0 | | 2.5 |
| 25 | | | -1.0 | 1.8 | 3.0 | 4.0 | 5.0 | | 2.6 |
| 26 | | | 1.5 | 4.5 | 5.0 | 8.0 | 6.0 | | 5.0 |
| 27 | | | 5.5 | 5.2 | 8.2 | 8.8 | 9.0 | 9.0 | 7.3 |
| 28 | 3.4 | 5.8 | 5.4 | 6.8 | 8.2 | 11.8 | 9.0 | 6.8 | 8.2 |
| 29 | 6.4 | 4.5 | 6.2 | 6.2 | 8.2 | 9.2 | 6.5 | | 7.3 |
| 30 | | | 4.8 | 6.8 | 11.4 | 11.5 | 8.5 | | 8.6 |
| July 1 | | | 11.8 | 12.0 | 10.5 | 13.0 | 7.2 | | 10.9 |
| 2 | | | 12.2 | 12.0 | 10.0 | 10.5 | 10.5 | | 11.0 |
| 3 | | | 9.0 | 6.0 | 8.8 | 9.2 | 11.4 | | 8.9 |
| 4 | | | 9.0 | 10.5 | 11.4 | 11.8 | 9.7 | | 10.5 |
| 5 | | | 7.2 | 7.0 | 11.2 | 9.8 | 9.2 | 8.0 | 8.9 |
| 6 | 7.0 | 7.8 | 5.7 | 6.4 | 9.2 | 8.6 | 8.2 | 5.0 | 7.6 |
| 7 | 5.0 | 5.4 | 6.4 | 5.0 | 8.6 | 6.2 | 7.0 | | 6.6 |
| 8 | | | 3.0 | 3.2 | 2.8 | 6.0 | 4.1 | | 3.8 |
| 9 | | | 5.1 | 5.7 | 5.1 | 6.2 | 4.8 | | 5.4 |
| 10 | | | 3.9 | 7.3 | 6.2 | 6.5 | 7.4 | | 6.3 |
| 11 | | | 6.4 | 9.1 | 5.9 | 8.2 | 8.8 | | 7.7 |
| 12 | | | 7.5 | 9.0 | M | 11.2 | 6.9 | | 8.4 |
| 13 | | | 2.2 | 2.2 | 3.3 | 3.0 | 3.9 | | 2.9 |
| 14 | | | M | M | M | 8.9 | 6.1 | | M |
| 15 | | | 4.4 | 5.0 | 4.7 | 7.8 | 7.8 | | 5.9 |
| 16 | | | 5.6 | 8.3 | M | 9.4 | 8.9 | | 8.0 |
| 17 | | | 6.1 | 9.4 | 11.7 | 14.2 | 8.9 | 10.6 | 10.1 |
| 18 | 4.4 | 6.7 | 6.1 | 4.4 | 7.2 | 6.1 | M | 5.0 | 6.0 |
| July 19 | 3.3 | 3.3 | 1.9 | 1.9 | | | | | |

TABLE 5

WET BULB TEMPERATURE (Degrees C)
GLACIER CAMP
1986 FIELD SEASON

| Mth/Day | 0100 | 0400 | 0700 | 1000 | 1300 | 1600 | 1900 | 2200 | Daytime Mean |
|---|---|---|---|---|---|---|---|---|---|
| June 20 | | | | | | | 3.3 | | |
| 21 | | | 1.7 | 2.8 | 2.8 | 2.8 | 2.2 | | 2.5 |
| 22 | | | 0.6 | 1.1 | 3.3 | 2.8 | 1.7 | | 1.9 |
| 23 | | | 0.0 | 1.1 | 1.1 | 2.2 | 2.2 | | 1.3 |
| 24 | | | 0.6 | 1.1 | 2.2 | 1.8 | 1.5 | | 1.4 |
| 25 | | | 0.0 | 0.0 | 1.8 | 1.5 | 2.2 | | 1.1 |
| 26 | | | -0.2 | 1.5 | 2.5 | 4.0 | 3.2 | | 2.2 |
| 27 | | | 2.5 | 3.0 | 3.2 | 4.5 | 2.5 | 2.5 | 3.1 |
| 28 | 1.0 | 2.2 | 2.2 | 2.2 | 3.4 | 6.2 | 4.6 | 4.0 | 3.7 |
| 29 | 3.6 | 3.0 | 3.0 | 3.6 | 5.6 | 5.4 | 4.5 | | 4.4 |
| 30 | | | 3.0 | 4.8 | 6.6 | 7.0 | 4.6 | | 5.2 |
| July 1 | | | 7.0 | 6.4 | 6.5 | 7.5 | 5.5 | | 6.6 |
| 2 | | | 8.2 | 8.0 | 6.8 | 8.8 | 6.8 | | 7.7 |
| 3 | | | 6.2 | 5.0 | 6.4 | 5.6 | 7.5 | | 6.1 |
| 4 | | | 5.5 | 7.5 | 7.6 | 5.8 | 6.8 | | 6.6 |
| 5 | | | 5.2 | 4.8 | 8.8 | 7.4 | 6.2 | 5.4 | 6.5 |
| 6 | 5.5 | 5.5 | 5.0 | 5.4 | 7.9 | 7.0 | 5.2 | 3.2 | 6.1 |
| 7 | 2.0 | 2.0 | 4.3 | 4.2 | 6.2 | 5.5 | 5.8 | | 5.2 |
| 8 | | | 3.0 | 2.8 | 2.8 | 5.8 | 3.4 | | 3.6 |
| 9 | | | 4.7 | 4.3 | 5.1 | 4.4 | 3.8 | | 4.5 |
| 10 | | | 3.0 | 4.9 | 5.3 | 4.4 | 5.0 | | 4.5 |
| 11 | | | 3.4 | 5.2 | 3.0 | 5.6 | 5.4 | | 4.5 |
| 12 | | | 6.8 | 6.7 | M | 6.7 | 5.7 | | 6.5 |
| 13 | | | 1.2 | 2.5 | 3.2 | 3.2 | 3.7 | | 2.8 |
| 14 | | | M | M | M | 6.5 | 4.5 | | M |
| 15 | | | 3.0 | 4.0 | 4.0 | 4.0 | 3.5 | | 3.7 |
| 16 | | | 2.0 | 4.0 | M | 6.0 | 6.0 | | 4.5 |
| 17 | | | 4.5 | 5.5 | 7.0 | 8.8 | 5.5 | 6.1 | 6.3 |
| 18 | 3.0 | 3.6 | 3.5 | 5.0 | 5.0 | 4.6 | M | 3.5 | 4.5 |
| July 19 | 3.5 | 2.5 | 2.5 | 1.7 | | | | | |

TABLE 6

DEW POINT (Degrees C)
GLACIER CAMP
1986 FIELD SEASON

| Mth/Day | 0100 | 0400 | 0700 | 1000 | 1300 | 1600 | 1900 | 2200 | Daytime Mean |
|---|---|---|---|---|---|---|---|---|---|
| June 20 | | | | | | | 3.3 | | |
| 21 | | | 1.1 | -1.1 | 1.7 | 1.1 | 1.1 | | 0.8 |
| 22 | | | -2.2 | -0.6 | -0.6 | -0.6 | 0.6 | | -0.7 |
| 23 | | | 0.0 | 0.6 | 0.0 | -0.6 | 2.2 | | 0.4 |
| 24 | | | 0.6 | -0.6 | -1.1 | 0.6 | 1.1 | | 0.1 |
| 25 | | | 0.0 | -2.2 | 0.6 | -1.1 | -1.1 | | -0.8 |
| 26 | | | -2.2 | -1.7 | 0.0 | -0.6 | 0.0 | | -0.9 |
| 27 | | | -0.6 | 0.0 | -2.8 | -0.6 | -5.0 | -5.0 | -1.8 |
| 28 | -1.7 | -1.7 | -1.7 | -3.3 | -1.7 | 0.0 | -0.6 | 1.1 | -1.5 |
| 29 | -0.6 | 1.1 | -1.1 | 0.0 | 2.8 | 1.7 | 2.2 | | 1.1 |
| 30 | | | 0.0 | 3.3 | 1.7 | 3.3 | 0.0 | | 1.7 |
| July 1 | | | 3.3 | 1.1 | 2.8 | 3.3 | 3.9 | | 2.9 |
| 2 | | | 5.0 | 3.9 | 3.3 | 7.8 | 2.8 | | 4.6 |
| 3 | | | 3.3 | 3.9 | 4.4 | 1.7 | 4.4 | | 3.5 |
| 4 | | | 2.2 | 5.6 | 4.4 | -1.1 | 3.3 | | 2.9 |
| 5 | | | 2.8 | 2.8 | 7.2 | 5.0 | 2.8 | 3.3 | 4.1 |
| 6 | 3.9 | 3.3 | 4.4 | 4.4 | 6.7 | 6.1 | 1.7 | 1.7 | 4.7 |
| 7 | -1.1 | -1.1 | 2.2 | 3.9 | 3.9 | 5.0 | 3.9 | | 3.8 |
| 8 | | | 2.8 | 2.2 | 2.8 | 5.0 | 2.8 | | 3.1 |
| 9 | | | 3.9 | 3.3 | 5.6 | 2.8 | 2.8 | | 3.7 |
| 10 | | | 1.7 | 2.8 | 3.9 | 2.2 | 2.8 | | 2.7 |
| 11 | | | -1.7 | 1.1 | -1.1 | 2.8 | 2.2 | | 0.7 |
| 12 | | | 5.6 | 4.4 | M | 2.2 | 4.4 | | 4.1 |
| 13 | | | 0.0 | 2.2 | 3.3 | 3.3 | 3.9 | | 2.5 |
| 14 | | | M | M | M | 4.4 | 2.8 | | M |
| 15 | | | 1.1 | 2.8 | 3.3 | -0.6 | -1.7 | | 1.0 |
| 16 | | | -1.7 | -1.1 | M | 2.8 | 3.3 | | 0.8 |
| 17 | | | 2.8 | 5.6 | 3.3 | 3.9 | 2.2 | 1.7 | 3.6 |
| 18 | 1.1 | -0.6 | 0.0 | 5.0 | 2.8 | 2.8 | M | 1.7 | 2.6 |
| July 19 | 3.3 | 1.1 | 1.1 | 1.7 | | | | | |

TABLE 7

RELATIVE HUMIDITY (%)
GLACIER CAMP
1986 FIELD SEASON

| Mth/Day | 0100 | 0400 | 0700 | 1000 | 1300 | 1600 | 1900 | 2200 | Daytime Mean |
|---|---|---|---|---|---|---|---|---|---|
| June 20 | | | | | | | 100 | | |
| 21 | | | 92 | 59 | 85 | 78 | 84 | | 80 |
| 22 | | | 69 | 77 | 60 | 65 | 84 | | 71 |
| 23 | | | 100 | 92 | 84 | 70 | 100 | | 89 |
| 24 | | | 100 | 77 | 64 | 84 | 100 | | 85 |
| 25 | | | 100 | 75 | 84 | 70 | 64 | | 79 |
| 26 | | | 75 | 64 | 71 | 56 | 66 | | 66 |
| 27 | | | 65 | 71 | 45 | 52 | 35 | 35 | 54 |
| 28 | 69 | 59 | 59 | 48 | 45 | 46 | 52 | 67 | 50 |
| 29 | 60 | 78 | 59 | 66 | 68 | 58 | 73 | | 65 |
| 30 | | | 71 | 80 | 51 | 56 | 57 | | 63 |
| July 1 | | | 56 | 47 | 60 | 53 | 80 | | 59 |
| 2 | | | 62 | 57 | 64 | 82 | 60 | | 65 |
| 3 | | | 69 | 86 | 75 | 58 | 61 | | 70 |
| 4 | | | 63 | 71 | 61 | 51 | 64 | | 62 |
| 5 | | | 73 | 73 | 77 | 70 | 64 | 74 | 71 |
| 6 | 80 | 74 | 93 | 86 | 81 | 87 | 62 | 79 | 82 |
| 7 | 64 | 59 | 73 | 93 | 74 | 93 | 80 | | 83 |
| 8 | | | 100 | 92 | 100 | 93 | 92 | | 95 |
| 9 | | | 93 | 86 | 100 | 79 | 85 | | 89 |
| 10 | | | 85 | 73 | 86 | 73 | 73 | | 78 |
| 11 | | | 60 | 57 | 59 | 68 | 63 | | 61 |
| 12 | | | 87 | 75 | M | 55 | 86 | | 76 |
| 13 | | | 84 | 100 | 100 | 100 | 100 | | 97 |
| 14 | | | M | M | M | 75 | 79 | | M |
| 15 | | | 78 | 85 | 92 | 56 | 50 | | 72 |
| 16 | | | 59 | 51 | M | 64 | 69 | | 61 |
| 17 | | | 79 | 75 | 56 | 50 | 63 | 54 | 65 |
| 18 | 78 | 60 | 66 | 100 | 73 | 79 | M | 79 | 80 |
| July 19 | 100 | 84 | 100 | 100 | | | | | |

TABLE 8

PRECIPITATION (MM)
GLACIER CAMP
1986 FIELD SEASON

| Mth/Day | 0100 | 0400 | 0700 | 1000 | 1300 | 1600 | 1900 | 2200 | Daily Total |
|---|---|---|---|---|---|---|---|---|---|
| June 20 | | | | | | | 0.0 | | 0.0 |
| 21 | | | 0.0 | 0.0 | 0.0 | 0.0 | 5.6 | | 5.6 |
| 22 | | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | | 0.0 |
| 23 | | | 60.0 | 15.0 | T | 1.5 | 1.5 | | 78.0 |
| 24 | | | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 | | 0.3 |
| 25 | | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | | 0.0 |
| 26 | | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | | 0.0 |
| 27 | | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 28 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 29 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | T | | 0.0 |
| 30 | | | 9.1 | 0.0 | 0.0 | 0.0 | 0.0 | | 9.1 |
| July 1 | | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | | 0.0 |
| 2 | | | T | 0.0 | 0.0 | 0.0 | 0.0 | | 0.0 |
| 3 | | | 1.8 | 0.0 | 0.0 | 0.0 | 0.0 | | 1.8 |
| 4 | | | 0.0 | 0.0 | 0.0 | T | 0.0 | | 0.0 |
| 5 | | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | T | T | 0.0 |
| 7 | 0.0 | 0.0 | 0.0 | 0.0 | T | T | 0.0 | | 0.0 |
| 8 | | | 0.0 | 0.0 | 0.5 | 0.5 | 0.0 | | 1.0 |
| 9 | | | T | 0.0 | 0.5 | 0.8 | 0.0 | | 1.3 |
| 10 | | | T | 0.0 | 0.3 | 0.0 | 0.0 | | 0.3 |
| 11 | | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | | 0.0 |
| 12 | | | 0.0 | 0.0 | 0.0 | 0.0 | 0.5 | | 0.5 |
| 13 | | | 7.1 | 1.8 | 0.8 | 4.6 | 3.0 | | 17.3 |
| 14 | | | 1.3 | 0.0 | 0.0 | 0.0 | 0.0 | | 1.3 |
| 15 | | | T | 0.0 | 0.0 | 0.0 | 0.0 | | 0.0 |
| 16 | | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | | 0.0 |
| 17 | | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 14.0 | 14.0 |
| 18 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 |
| July 19 | 1.3 | 0.5 | T | T | | | | | 1.8 |
| | | | | | | | | Total | 132.6 |

TABLE 9

WIND SPEED (Meters/Second)
GLACIER CAMP
1986 FIELD SEASON

| Mth/Day | 0100 | 0400 | 0700 | 1000 | 1300 | 1600 | 1900 | 2200 | Daytime Mean |
|---|---|---|---|---|---|---|---|---|---|
| June 20 | | | | | | | 0.7 | | |
| 21 | | | 2.3 | 0.0 | 0.0 | 1.6 | 2.4 | | 1.3 |
| 22 | | | 2.3 | 3.0 | 1.2 | 1.9 | 1.3 | | 1.9 |
| 23 | | | 3.0 | 0.6 | 0.6 | 0.8 | 0.1 | | 1.0 |
| 24 | | | 1.0 | 1.9 | 1.1 | 0.8 | 2.2 | | 1.4 |
| 25 | | | 0.7 | 0.1 | 1.2 | 1.3 | 1.4 | | 0.9 |
| 26 | | | 2.0 | 1.3 | 2.9 | 1.8 | 2.7 | | 2.1 |
| 27 | | | 1.8 | 2.7 | 3.4 | 3.8 | 2.3 | 1.8 | 2.8 |
| 28 | 3.6 | 2.5 | 1.9 | 4.4 | 5.8 | 3.9 | 2.9 | 1.1 | 3.8 |
| 29 | 3.1 | 2.1 | 1.6 | 3.7 | 3.4 | 4.6 | 2.8 | | 3.2 |
| 30 | | | 2.2 | 1.6 | 1.9 | 4.1 | 3.0 | | 2.6 |
| July 1 | | | 2.6 | 5.0 | 3.9 | 3.9 | 5.0 | | 4.1 |
| 2 | | | 3.3 | 2.1 | 4.0 | 6.2 | 7.0 | | 4.5 |
| 3 | | | 2.1 | 5.1 | 5.0 | 2.8 | 3.4 | | 3.7 |
| 4 | | | 2.5 | 1.8 | 2.6 | 2.6 | 2.9 | | 2.5 |
| 5 | | | 3.3 | 3.3 | 2.7 | 4.6 | 5.4 | 4.9 | 3.9 |
| 6 | 3.7 | 4.3 | 2.8 | 3.7 | 2.8 | 4.7 | 3.8 | 3.8 | 3.6 |
| 7 | 2.6 | 1.9 | 2.1 | 1.0 | 3.6 | 3.2 | 2.9 | | 2.6 |
| 8 | | | 1.9 | 3.0 | 3.4 | 1.5 | 1.6 | | 2.3 |
| 9 | | | 0.0 | 2.6 | 0.7 | 2.8 | 4.1 | | 2.0 |
| 10 | | | 3.8 | 4.4 | 8.4 | 6.1 | 6.1 | | 5.8 |
| 11 | | | 0.6 | 1.8 | 4.5 | 4.7 | 3.1 | | 2.9 |
| 12 | | | 2.4 | 0.9 | M | 2.8 | 2.8 | | 2.2 |
| 13 | | | 2.8 | 0.9 | 1.5 | 2.3 | 1.6 | | 1.8 |
| 14 | | | 2.5 | M | 3.4 | 0.6 | 2.2 | | 2.2 |
| 15 | | | 3.8 | 1.5 | 4.1 | 3.0 | 5.0 | | 3.5 |
| 16 | | | 1.4 | 4.0 | M | 4.5 | 1.9 | | 3.0 |
| 17 | | | 3.5 | 4.3 | 1.1 | 3.9 | 1.9 | 6.7 | 2.9 |
| 18 | 2.9 | 2.2 | 1.0 | 3.8 | 2.7 | 3.7 | M | 2.9 | 2.8 |
| July 19 | 1.5 | 5.2 | 0.8 | 2.7 | | | | | |

TABLE 10

WIND DIRECTION (360 Degree Azimuth)
GLACIER CAMP
1986 FIELD SEASON

| Mth/Day | 0100 | 0400 | 0700 | 1000 | 1300 | 1600 | 1900 | 2200 | Prevailing Daytime Wind |
|---|---|---|---|---|---|---|---|---|---|
| June 20 | | | | | | | 340 | | |
| 21 | | | 340 | None | None | 360 | 340 | | 340 |
| 22 | | | 160 | 160 | 360 | 360 | 340 | | 160 |
| 23 | | | 160 | 160 | 135 | 340 | 45 | | 160 |
| 24 | | | 315 | 360 | 340 | 340 | 340 | | 340 |
| 25 | | | 340 | 160 | 360 | 340 | 360 | | 350 |
| 26 | | | 360 | 360 | 340 | 340 | 340 | | 340 |
| 27 | | | 340 | 340 | 340 | 340 | 340 | 340 | 340 |
| 28 | 340 | 340 | 360 | 360 | 340 | 340 | 315 | 340 | 350 |
| 29 | 340 | 360 | 340 | 340 | 340 | 340 | 315 | | 340 |
| 30 | | | 340 | 340 | 340 | 340 | 315 | | 340 |
| July 1 | | | 45 | 45 | 315 | 225 | 340 | | 45 |
| 2 | | | 90 | 90 | 315 | 340 | 340 | | |
| 3 | | | 315 | 340 | 340 | 340 | 20 | | 340 |
| 4 | | | 360 | 360 | 360 | 360 | 315 | | 360 |
| 5 | | | 315 | 340 | 360 | 340 | 340 | 340 | 340 |
| 6 | 340 | 340 | 340 | 340 | 360 | 340 | 315 | 340 | 340 |
| 7 | 315 | 340 | 340 | 340 | 340 | 315 | 160 | | 340 |
| 8 | | | 340 | 315 | 315 | 315 | 340 | | 315 |
| 9 | | | 360 | 340 | 340 | 315 | 340 | | 340 |
| 10 | | | 340 | 338 | 360 | 360 | 360 | | 360 |
| 11 | | | 340 | 340 | 315 | 340 | 360 | | 340 |
| 12 | | | 340 | 45 | M | 90 | 360 | | |
| 13 | | | 340 | 360 | 225 | 180 | 360 | | 360 |
| 14 | | | 340 | M | 340 | 340 | 340 | | 340 |
| 15 | | | 180 | 180 | 180 | 180 | 180 | | 180 |
| 16 | | | 340 | 45 | M | 360 | 340 | | 340 |
| 17 | | | 340 | 340 | 180 | 45 | 360 | 90 | 340 |
| 18 | 340 | 340 | 360 | 340 | 340 | 340 | M | 360 | 340 |
| July 19 | 45 | 360 | 360 | 340 | | | | | |

TABLE 11

CLOUD COVER (Tenths)
GLACIER CAMP
1986 FIELD SEASON

| Mth/Day | 0100 | 0400 | 0700 | 1000 | 1300 | 1600 | 1900 | 2200 | Daytime Mean |
|---|---|---|---|---|---|---|---|---|---|
| June 20 | | | | | | | 10 | | |
| 21 | | | 10 | 10 | 10 | 10 | 10 | | 10.0 |
| 22 | | | 10 | 10 | 6 | 10 | 10 | | 9.2 |
| 23 | | | 10 | 10 | 10 | 10 | 10 | | 10.0 |
| 24 | | | 10 | 4 | 10 | 8 | 9 | | 8.2 |
| 25 | | | 0 | 3 | 10 | 10 | 10 | | 6.6 |
| 26 | | | 0 | 0 | 1 | 2 | 4 | | 1.4 |
| 27 | | | 1 | 3 | 1 | 1 | 2 | 0 | 1.6 |
| 28 | 2 | 2 | 0 | 0 | 0 | 4 | 6 | 2 | 2.0 |
| 29 | 1 | 1 | 1 | 3 | 4 | 1 | 9 | | 3.6 |
| 30 | | | 2 | 1 | 4 | 1 | 3 | | 2.2 |
| July 1 | | | 4 | 9 | 10 | 5 | 4 | | 6.4 |
| 2 | | | 4 | 9 | 4 | 3 | 3 | | 4.6 |
| 3 | | | 9 | 8 | 2 | 7 | 5 | | 6.2 |
| 4 | | | 1 | 0 | 6 | 7 | 4 | | 3.6 |
| 5 | | | 2 | 1 | 5 | 5 | 8 | 1 | 4.2 |
| 6 | 0 | 1 | 1 | 0 | 1 | 3 | 8 | 2 | 2.6 |
| 7 | 0 | 2 | >1 | 6 | 2 | 9 | 10 | | 7.4 |
| 8 | | | 10 | >9 | 10 | 10 | 10 | | 9.8 |
| 9 | | | 9 | 8 | 10 | 6 | 8 | | 8.2 |
| 10 | | | 10 | 10 | 8 | 2 | 1 | | 6.2 |
| 11 | | | 3 | 1 | 5 | 10 | 3 | | 4.4 |
| 12 | | | 1 | 4 | M | 10 | 10 | | 6.2 |
| 13 | | | 10 | 10 | 10 | 10 | 9 | | 9.8 |
| 14 | | | 0 | M | 5 | 8 | 10 | | 5.8 |
| 15 | | | 8 | 8 | 9 | 9 | 7 | | 8.2 |
| 16 | | | 8 | 10 | M | 5 | 3 | | 6.5 |
| 17 | | | 4 | 6 | 3 | 3 | 9 | 10 | 5.0 |
| 18 | 10 | 5 | 6 | 1.5 | 9 | 10 | 10 | 10 | 7.3 |
| July 19 | 10 | 10 | 10 | 10 | | | | | |

TABLE 12

ESTIMATED CEILING OF CLOUD COVER (Meters)
GLACIER CAMP
1986 FIELD SEASON

| Mth/Day | 0100 | 0400 | 0700 | 1000 | 1300 | 1600 | 1900 | 2200 | Average Ceiling |
|---|---|---|---|---|---|---|---|---|---|
| June 20 | | | | | | | 0 | | |
| 21 | | | 300 | 250 | 300 | 250 | 450 | | 310 |
| 22 | | | 900 | 750 | 900 | 850 | 850 | | 850 |
| 23 | | | 0 | 0 | 0 | 350 | 150 | | 100 |
| 24 | | | 50 | 1200 | 900 | 1200 | 900 | | 850 |
| 25 | | | Clear | 3000 | 1200 | 900 | 2400 | | 1875 |
| 26 | | | Clear | Clear | Clear | 300 | 3000 | | 1650 |
| 27 | | | 4500 | 4500 | 3600 | 3600 | 3600 | | 3960 |
| 28 | Clear | Clear | Clear | Clear | Clear | 3000 | 2100 | 2100 | 2550 |
| 29 | 4500 | 4500 | 4500 | 3000 | 4500 | 2100 | 1800 | 1800 | 3180 |
| 30 | | | 1500 | 1500 | 1500 | 1500 | 1500 | | 1500 |
| July 1 | | | 3000 | 2100 | 2100 | 2100 | 1500 | | 2160 |
| 2 | | | 2100 | 2100 | 2100 | 2100 | 2100 | | 2100 |
| 3 | | | 2100 | 1800 | 1800 | 2100 | 2100 | | 1980 |
| 4 | | | 3000 | Clear | 2100 | 2100 | 2100 | | 1860 |
| 5 | | | Clear | 4200 | 2400 | 2400 | 2400 | 2400 | 2850 |
| 6 | Clear | 3000 | 4500 | Clear | 4500 | 2100 | 1800 | 2400 | 3225 |
| 7 | Clear | Clear | Clear | 1500 | 1500 | 900 | 450 | | 1100 |
| 8 | | | 0 | 1500 | 150 | 150 | 2400 | | 840 |
| 9 | | | 1500 | 900 | 150 | 2400 | 150 | | 1020 |
| 10 | | | 1500 | 600 | 600 | 600 | 2100 | | 1080 |
| 11 | | | 1200 | 2100 | 1500 | 2100 | 2100 | | 1800 |
| 12 | | | 1200 | 1500 | M | 1500 | 900 | | 1275 |
| 13 | | | 600 | 450 | 450 | 300 | 600 | | 480 |
| 14 | | | Clear | M | 3000 | 2400 | 2400 | | 2600 |
| 15 | | | 900 | 900 | 1800 | 3000 | 3000 | | 1920 |
| 16 | | | 2700 | 2400 | M | 2400 | 2400 | | 2475 |
| 17 | | | 2400 | 3600 | 2400 | 2400 | 2400 | 1500 | 2640 |
| 18 | 1800 | 1800 | 1800 | 1800 | 900 | 1800 | 1800 | 1800 | 1620 |
| July 19 | 1200 | 450 | 1200 | 100 | | | | | |

TABLE 13

CLOUD TYPE
GLACIER CAMP
1986 FIELD SEASON

| Mth/Day | 0700 | 1000 | 1300 | 1600 | 1900 |
|---|---|---|---|---|---|
| June 20 | | | | | Fog |
| 21 | St | St | St | St | St |
| 22 | St | St | Ac3/Cu3 | St | St |
| 23 | Fog | Fog | Fog | Fog | St |
| 24 | St | Ci1/Cu1/Sc2 | Sc | Sc | Sc |
| 25 | Clear | Sc | Sc | Sc | Sc |
| 26 | Clear | Cu | Cu | Ci1/Cu1 | Cu |
| 27 | Ci | Ci | Cu | Cu | Cu |
| 28 | Clear | Clear | Clear | Cu | Ci2/Cu4 |
| 29 | Ci1 | As1/Ci1/Cu1 | Ci1/Cu | Ci3/Cu1 | Sc8/St1/Ci1 |
| 30 | St1/Cu1 | Sc | Cu3/Ci1 | Cu1 | Cu1/Ac2 |
| July 1 | Ci3/Cs1 | Sc | Sc | Cu3/Ci2 | Ci2/Cu2 |
| 2 | Sc3/Cu1 | Sc | Cu2/St2 | Cu | Ci2/Cu1 |
| 3 | Sc | Sc | Sc | Cu3/Ci4 | Cu4/Ci1 |
| 4 | Cu | Clear | Cu | Sc5/Cu2 | Cu4 |
| 5 | Clear | Cu | Cu | Cu | Sc |
| 6 | Ci | Clear | Ci | Cu | Sc |
| 7 | Cu | Ci3/Ac2/Sc1 | Ci1/Cu1 | Sc | St |
| 8 | Fog/Cu | Fog/Sc | Ns2/Sc8 | Ns1/Sc9 | St |
| 9 | St9 | Sc1/Ac7 | St | Sc5/Ac1 | Scud/Ac7 |
| 10 | St | Scud/Ac4 | Scud/Cu7 | CapCloud/Sc2 | Sc1 |
| 11 | Ac1/Cu2 | Ac | Sc | Ac9/Sc1 | Ac2/Ci1 |
| 12 | Cu | Ci3/Cu1 | M | As9/Cu1 | St |
| 13 | St | St | St/Sc | St | Sc |
| 14 | M | M | Sc2/Ci3 | Sc4/Cu4 | St |
| 15 | Cf | Sc | St7/Cu1/Ci1 | Cu | Sc3/Ci4 |
| 16 | Cf4/St4 | St | M | St2/Cu3 | Cu |
| 17 | Cu | Ci | Ci1/Cu2 | Cu | Sc |
| 18 | Cu | Cu1/Ac1 | Ac4/Sc5 | St8/Sc2 | St5/Cu5 |
| July 19 | St | St | | | |

TABLE 14

CLOUD MOVEMENT (360 Degree Azimuth)
GLACIER CAMP
1986 FIELD SEASON

| Mth/Day | 0100 | 0400 | 0700 | 1000 | 1300 | 1600 | 1900 | 2200 | Daytime Mode |
|---|---|---|---|---|---|---|---|---|---|
| June 20 | | | | | | | 0 | | |
| 21 | | | 360 | 180 | 90 | 90 | 360 | | 90/360 |
| 22 | | | 270 | 270 | 270 | 270 | 270 | | 270 |
| 23 | | | 0 | 0 | 0 | 0 | 0 | | 0 |
| 24 | | | 0 | 270 | 270 | 270 | 270 | | 270 |
| 25 | | | 0 | 135 | 270 | 270 | 270 | | 270 |
| 26 | | | 0 | 0 | 225 | 225 | 225 | | 225 |
| 27 | | | 270 | 270 | 270 | 270 | 225 | 0 | 270 |
| 28 | 0 | 0 | 0 | 0 | 0 | 135 | 225 | 225 | 0 |
| 29 | 225 | 225 | 0 | 90 | 315 | 180 | 135 | | |
| 30 | | | 135 | 90 | 90 | 90 | 135 | | 90 |
| July 1 | | | 135 | 90 | 135 | 135 | 135 | | 135 |
| 2 | | | 90 | 90 | 90 | 135 | 90 | | 90 |
| 3 | | | 45 | 315 | 315 | 90 | 90 | | 90/315 |
| 4 | | | 360 | 0 | 315 | 315 | 315 | | 315 |
| 5 | | | 0 | 135 | 180 | 180 | 135 | 135 | 135 |
| 6 | 0 | 90 | 315 | 0 | 0 | 135 | 135 | 90 | 0 |
| 7 | 0 | 0 | 90 | 90 | 90 | 90 | 225 | | 90 |
| 8 | | | 360 | 360 | 360 | 360 | 180 | | 360 |
| 9 | | | 180 | 180 | 180 | 135 | 360 | | 180 |
| 10 | | | 90 | 90 | 360 | 360 | 90 | | 90 |
| 11 | | | 315 | 270 | 225 | 315 | 315 | | 315 |
| 12 | | | 270 | 135 | M | 135 | 135 | | 135 |
| 13 | | | 225 | 225 | 225 | 225 | 202.5 | | 225 |
| 14 | | | 0 | M | 180 | 180 | 135 | | 180 |
| 15 | | | 180 | 180 | 180 | 180 | 225 | | 180 |
| 16 | | | 135 | 180 | M | 135 | 135 | | 135 |
| 17 | | | 135 | 135 | 135 | 135 | 180 | 225 | 135 |
| 18 | 225 | 225 | 225 | 225 | 225 | 270 | 270 | 270 | 225 |
| July 19 | 270 | 270 | 270 | 270 | | | | | 270 |

TABLE 15

VISIBILITY TO SOUTH (KM)
GLACIER CAMP
1986 FIELD SEASON

| Mth/Day | 0100 | 0400 | 0700 | 1000 | 1300 | 1600 | 1900 | 2200 | Mean Visibility Daytime |
|---|---|---|---|---|---|---|---|---|---|
| June 20 | | | | | | | M | | |
| 21 | | | M | >100 | 5.0 | >100 | 15.0 | | 55.0 |
| 22 | | | >100 | >100 | 5.0 | 5.0 | 5.0 | | 43.0 |
| 23 | | | 0.2 | 0.8 | 4.0 | 5.0 | 4.0 | | 2.8 |
| 24 | | | 3.0 | 100.0 | 100.0 | 100.0 | 100.0 | | 80.6 |
| 25 | | | >120 | 120.0 | 120.0 | 120.0 | 120.0 | | 120.0 |
| 26 | | | >150 | >150 | >150 | >150 | 150.0 | | 150.0 |
| 27 | | | 150.0 | 150.0 | 150.0 | >150 | >150 | >150 | 150.0 |
| 28 | >150 | >150 | >150 | >150 | >150 | >150 | 120.0 | 120.0 | 144.0 |
| 29 | 120.0 | 120.0 | 150.0 | 125.0 | 120.0 | 100.0 | 80.0 | | 115.0 |
| 30 | | | 120.0 | 120.0 | 120.0 | 120.0 | 120.0 | | 120.0 |
| July 1 | | | 80.0 | 110.0 | 80.0 | 100.0 | 120.0 | | 98.0 |
| 2 | | | 80.0 | 65.0 | 50.0 | 80.0 | 80.0 | | 71.0 |
| 3 | | | 30.0 | 30.0 | 50.0 | 30.0 | 50.0 | | 38.0 |
| 4 | | | 50.0 | 50.0 | 50.0 | 30.0 | 50.0 | | 46.0 |
| 5 | | | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 |
| 6 | 30.0 | 30.0 | 50.0 | 30.0 | 30.0 | 40.0 | 50.0 | 50.0 | 40.0 |
| 7 | 40.0 | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 | | 50.0 |
| 8 | | | 0.8 | 50.0 | 30.0 | 30.0 | 100.0 | | 42.2 |
| 9 | | | 50.0 | 50.0 | 8.0 | 50.0 | 50.0 | | 41.6 |
| 10 | | | 30.0 | 50.0 | 30.0 | 30.0 | 50.0 | | 38.0 |
| 11 | | | 120.0 | 30.0 | 30.0 | 25.0 | 25.0 | | 46.0 |
| 12 | | | 30.0 | 25.0 | M | 15.0 | 15.0 | | 21.2 |
| 13 | | | 50.0 | 50.0 | 50.0 | 30.0 | 110.0 | | 58.0 |
| 14 | | | M | M | 80.0 | 65.0 | 100.0 | | 81.7 |
| 15 | | | 150.0 | 50.0 | 80.0 | 120.0 | 120.0 | | 104.0 |
| 16 | | | 120.0 | M | M | 110.0 | 120.0 | | 116.7 |
| 17 | | | 50.0 | 50.0 | 50.0 | 50.0 | 100.0 | 50.0 | 60.0 |
| 18 | 40.0 | 100.0 | 150.0 | 120.0 | 80.0 | 50.0 | 30.0 | 50.0 | 86.0 |
| July 19 | 25.0 | 50.0 | 50.0 | 50.0 | | | | | |

TABLE 16

VISIBILITY TO NORTH (KM)
GLACIER CAMP
1986 FIELD SEASON

| Mth/Day | 0100 | 0400 | 0700 | 1000 | 1300 | 1600 | 1900 | 2200 | Mean Visibility Daytime |
|---|---|---|---|---|---|---|---|---|---|
| June 20 | | | | | | | M | | |
| 21 | | | M | 0.3 | 2.5 | 1.5 | 2.5 | | 1.7 |
| 22 | | | >3 | 2.5 | >3 | 2.5 | 2.5 | | 2.7 |
| 23 | | | 0.2 | 0.8 | 0.8 | 2.0 | 2.5 | | 1.3 |
| 24 | | | 0.8 | >3 | >3 | >3 | >3 | | 2.6 |
| 25 | | | >3 | >3 | >3 | >3 | >3 | | 3.0 |
| 26 | | | >3 | >3 | >3 | >3 | >3 | | 3.0 |
| 27 | | | >3 | >3 | >3 | >3 | >3 | >3 | 3.0 |
| 28 | >3 | >3 | >3 | >3 | >3 | >3 | >3 | >3 | 3.0 |
| 29 | >3 | >3 | >3 | >3 | >3 | >3 | >3 | | 3.0 |
| 30 | | | >3 | >3 | >3 | >3 | >3 | | 3.0 |
| July 1 | | | >3 | >3 | >3 | >3 | >3 | | 3.0 |
| 2 | | | >3 | >3 | >3 | >3 | >3 | | 3.0 |
| 3 | | | >3 | >3 | >3 | >3 | >3 | | 3.0 |
| 4 | | | >3 | >3 | >3 | >3 | >3 | | 3.0 |
| 5 | | | >3 | >3 | >3 | >3 | >3 | >3 | 3.0 |
| 6 | >3 | >3 | >3 | >3 | >3 | >3 | >3 | >3 | 3.0 |
| 7 | >3 | >3 | >3 | >3 | >3 | >3 | 2.5 | | 2.9 |
| 8 | | | 0.5 | >3 | 2.5 | 2.5 | >3 | | 2.3 |
| 9 | | | >3 | >3 | 0.8 | >3 | 2.5 | | 2.5 |
| 10 | | | >3 | 2.5 | 1.5 | 3.0 | >3 | | 2.6 |
| 11 | | | >3 | >3 | >3 | >3 | >3 | | 3.0 |
| 12 | | | >3 | >3 | M | >3 | 3.0 | | 3.0 |
| 13 | | | 3.0 | 3.0 | 1.5 | 1.2 | 2.5 | | 2.2 |
| 14 | | | M | M | >3 | >3 | >3 | | 3.0 |
| 15 | | | 2.5 | 2.5 | >3 | >3 | >3 | | 2.8 |
| 16 | | | >3 | M | M | >3 | >3 | | 3.0 |
| 17 | | | >3 | >3 | >3 | >3 | >3 | >3 | 3.0 |
| 18 | 3.0 | >3 | >3 | >3 | >3 | >3 | >3 | >3 | 3.0 |
| July 19 | >3 | 2.5 | 3.0 | 1.5 | | | | | |

TABLE 17

DAILY MAXIMUM TEMPERATURE (Degrees C)
TUNDRA CAMP
1987 FIELD SEASON

| Mth/Day | 0300 | 0600 | 0900 | 1200 | 1500 | 1800 | 2100 | 0000 | Absolute Daily Maximum |
|---|---|---|---|---|---|---|---|---|---|
| June 28 | | | | | | 11.7 | | | 11.7 |
| 29 | | | 11.1 | | | | 17.8 | | 17.8 |
| 30 | | | | | | 20.0 | | | 20.0 |
| July 1 | | 12.2 | | | | | | | 12.2 |
| 2 | | | | | | | | | |
| 3 | | | | | | | | | |
| 4 | | | | | | | | | |
| 5 | | | | | | | | | |
| 6 | | | | | | 12.2 | | | 12.2 |
| 7 | | | 8.9 | | | 9.4 | | | 9.4 |
| 8 | | 8.3 | | | | 15.6 | | | 15.6 |
| 9 | | | 16.7 | | | | 18.9 | | 18.9 |
| 10 | | | | 12.2 | | 17.8 | | | 17.8 |
| 11 | | | 10.0 | 13.9 | 14.4 | 14.4 | 11.1 | | 14.4 |
| 12 | | | | 10.6 | | 7.8 | | | 10.6 |
| 13 | | | 6.7 | | | | 15.0 | | 15.0 |
| 14 | | | 7.8 | | | 10.0 | | | 10.0 |
| 15 | | | 8.3 | | | 8.9 | | | 8.9 |
| 16 | | | 10.0 | | | 12.2 | | | 12.2 |
| 17 | | | | 8.9 | | | 12.8 | | 12.8 |
| 18 | | | 12.2 | | | | 12.2 | | 12.2 |
| 19 | | | 11.7 | | | | 16.7 | | 16.7 |
| 20 | | | 14.4 | | | | 23.4 | | 23.4 |
| 21 | | | | 13.9 | | 22.2 | | | 22.2 |
| 22 | | | | | 13.3 | | | | 13.3 |
| 23 | | 6.7 | | | | | 13.9 | | 13.9 |
| 24 | | | | | | | | 20.6 | 20.6 |
| 25 | | | 9.4 | | | 15.0 | | | 15.0 |
| July 26 | | 11.1 | | | | | 20.0 | | 20.0 |

TABLE 18

DAILY MINIMUM TEMPERATURE (Degrees C)
TUNDRA CAMP
1987 FIELD SEASON

| Mth/Day | 0300 | 0600 | 0900 | 1200 | 1500 | 1800 | 2100 | 0000 | Absolute Daily Minimum |
|---|---|---|---|---|---|---|---|---|---|
| June 28 | | | | 2.2 | | 5.0 | | | 2.2 |
| 29 | | | 5.0 | | | | 6.7 | | 5.0 |
| 30 | | | 6.1 | | | 8.9 | | | 6.1 |
| July 1 | | 6.1 | | | | M | | | 6.1 |
| 2 | | | 6.7 | | 9.4 | 12.8 | 12.8 | 9.4 | 6.7 |
| 3 | 8.3 | 7.8 | 7.8 | 13.9 | 13.3 | 14.4 | | | 7.8 |
| 4 | | | 7.8 | | | | 16.7 | | 7.8 |
| 5 | | | 7.2 | 12.8 | 14.4 | 15.0 | 16.7 | 8.9 | 7.2 |
| 6 | | | 6.1 | | | 6.7 | | | 6.1 |
| 7 | | | 3.3 | | | 5.0 | | | 3.3 |
| 8 | | 4.4 | | | | 3.3 | | | 3.3 |
| 9 | | | 5.0 | | | | 7.8 | | 5.0 |
| 10 | | | | 5.6 | | 9.4 | | | 5.6 |
| 11 | | | 5.0 | 7.8 | 12.2 | 10.0 | 9.4 | | 5.0 |
| 12 | | | | 3.3 | | 4.4 | | | 3.3 |
| 13 | | | 3.3 | | | | 5.6 | | 3.3 |
| 14 | | | 4.4 | | | 3.3 | | | 3.3 |
| 15 | | | M | | | 7.2 | | | 7.2 |
| 16 | | | 6.7 | | | 7.8 | | | 6.7 |
| 17 | | | | 4.4 | | | 8.9 | | 4.4 |
| 18 | | | 6.7 | | | | 7.8 | | 6.7 |
| 19 | | | 6.7 | | | | 7.8 | | 6.7 |
| 20 | | | 8.9 | | | | 10.0 | | 8.9 |
| 21 | | | | 6.7 | | 11.7 | | | 6.7 |
| 22 | | | | | 6.1 | | | | 6.1 |
| 23 | | 1.7 | | | | | 4.4 | | 1.7 |
| 24 | | | | | | | 5.6 | | 5.6 |
| 25 | | | 6.1 | | | | 6.1 | | 6.1 |
| July 26 | | 4.4 | | | | | 5.6 | | 4.4 |

TABLE 19

DRY BULB TEMPERATURE (Degrees C)
TUNDRA CAMP
1987 FIELD SEASON

| Mth/Day | 0300 | 0600 | 0900 | 1200 | 1500 | 1800 | 2100 | 0000 | Daily Average |
|---|---|---|---|---|---|---|---|---|---|
| June 28 | | | | 6.5 | | 7.5 | | | 7.0 |
| 29 | | | 9.0 | | | | 12.5 | | 10.8 |
| 30 | | | 9.0 | | | 16.5 | | | 12.8 |
| July 1 | | 9.5 | | | | 14.0 | | | 11.8 |
| 2 | | | 9.5 | | 14.5 | 18.5 | 13.5 | 11.5 | 13.5 |
| 3 | 10.5 | 9.5 | 10.0 | 15.0 | 17.5 | 15.0 | | | 12.9 |
| 4 | | | 12.0 | | | | 13.0 | | 12.5 |
| 5 | | | 13.0 | 17.5 | 19.5 | 15.5 | 12.5 | 11.0 | 14.8 |
| 6 | | | 8.5 | | | 6.5 | | | 7.5 |
| 7 | | | 5.5 | | | 6.5 | | | 6.0 |
| 8 | | 5.5 | | | | 12.0 | | | 8.8 |
| 9 | | | 9.0 | | | | 10.5 | | 9.8 |
| 10 | | | | 10.0 | | 11.5 | | | 10.8 |
| 11 | | | 8.0 | 11.5 | 12.0 | 10.5 | 9.5 | | 10.3 |
| 12 | | | | 5.5 | | | | | 5.5 |
| 13 | | | | | | | | | |
| 14 | | | | | | | | | |
| 15 | | | | | | | | | |
| 16 | | | | | | | | | |
| 17 | | | | | | | | | |
| 18 | | | | | | | | | |
| 19 | | | | | | | | | |
| 20 | | | | | | | | | |
| 21 | | | | | | | | | |
| 22 | | | | | | | | | |
| 23 | | | | | | | | | |
| 24 | | | | | | | | | |
| 25 | | | | | | | | | |
| July 26 | | | | | | | | | |

TABLE 20

WET BULB TEMPERATURE (Degrees C)
TUNDRA CAMP
1987 FIELD SEASON

| Mth/Day | 0300 | 0600 | 0900 | 1200 | 1500 | 1800 | 2100 | 0000 | Daily Average |
|---|---|---|---|---|---|---|---|---|---|
| June 28 | | | | 5.0 | | 5.5 | | | 5.3 |
| 29 | | | 7.0 | | | | 9.5 | | 8.3 |
| 30 | | | 7.0 | | | 9.0 | | | 8.0 |
| July 1 | | 5.5 | | | | 9.0 | | | 7.3 |
| 2 | | | 7.0 | | 10.0 | 11.0 | 8.5 | 8.0 | 8.9 |
| 3 | 7.5 | 6.5 | 7.5 | 9.5 | 10.5 | 9.5 | | | 8.5 |
| 4 | | | 8.0 | | | | 11.0 | | 9.5 |
| 5 | | | 6.5 | 9.0 | 10.5 | 9.5 | 9.5 | 7.5 | 8.8 |
| 6 | | | 6.5 | | | 6.5 | | | 6.5 |
| 7 | | | 4.0 | | | 6.0 | | | 5.0 |
| 8 | | 4.0 | | | | 8.0 | | | 6.0 |
| 9 | | | 6.0 | | | | 7.5 | | 6.8 |
| 10 | | | | 6.5 | | 7.0 | | | 6.8 |
| 11 | | | 6.0 | 7.0 | 7.0 | 6.0 | 6.0 | | 6.4 |
| 12 | | | | 5.5 | | | | | 5.5 |
| 13 | | | | | | | | | |
| 14 | | | | | | | | | |
| 15 | | | | | | | | | |
| 16 | | | | | | | | | |
| 17 | | | | | | | | | |
| 18 | | | | | | | | | |
| 19 | | | | | | | | | |
| 20 | | | | | | | | | |
| 21 | | | | | | | | | |
| 22 | | | | | | | | | |
| 23 | | | | | | | | | |
| 24 | | | | | | | | | |
| 25 | | | | | | | | | |
| July 26 | | | | | | | | | |

TABLE 21

DEW POINT (Degrees C)
TUNDRA CAMP
1987 FIELD SEASON

| Mth/Day | 0300 | 0600 | 0900 | 1200 | 1500 | 1800 | 2100 | 0000 | Daily Average |
|---|---|---|---|---|---|---|---|---|---|
| June 28 | | | | 3.8 | | 3.3 | | | 3.6 |
| 29 | | | 5.0 | | | | 6.1 | | 5.6 |
| 30 | | | 5.0 | | | 1.1 | | | 3.1 |
| July 1 | | 1.1 | | | | 4.4 | | | 2.8 |
| 2 | | | 4.4 | | 6.1 | 5.0 | 3.3 | 4.4 | 4.6 |
| 3 | 4.4 | 3.8 | 5.0 | 4.4 | 5.0 | 4.4 | | | 4.5 |
| 4 | | | 3.8 | | | | 9.4 | | 6.6 |
| 5 | | | -1.1 | 1.1 | 2.2 | 3.8 | 6.6 | 3.8 | 2.7 |
| 6 | | | 4.4 | | | 6.6 | | | 5.5 |
| 7 | | | 2.2 | | | 5.6 | | | 3.9 |
| 8 | | 2.2 | | | | 3.3 | | | 2.8 |
| 9 | | | 3.3 | | | | 5.0 | | 4.2 |
| 10 | | | | 3.3 | | 2.8 | | | 3.1 |
| 11 | | | 4.4 | 1.1 | 0.6 | 1.7 | 2.2 | | 2.0 |
| 12 | | | | 5.5 | | | | | 5.5 |
| 13 | | | | | | | | | |
| 14 | | | | | | | | | |
| 15 | | | | | | | | | |
| 16 | | | | | | | | | |
| 17 | | | | | | | | | |
| 18 | | | | | | | | | |
| 19 | | | | | | | | | |
| 20 | | | | | | | | | |
| 21 | | | | | | | | | |
| 22 | | | | | | | | | |
| 23 | | | | | | | | | |
| 24 | | | | | | | | | |
| 25 | | | | | | | | | |
| July 26 | | | | | | | | | |

TABLE 22

RELATIVE HUMIDITY (%)
TUNDRA CAMP
1987 FIELD SEASON

| Mth/Day | 0300 | 0600 | 0900 | 1200 | 1500 | 1800 | 2100 | 0000 | Daily Average |
|---|---|---|---|---|---|---|---|---|---|
| June 28 | | | | 82 | | 70 | | | 76 |
| 29 | | | 77 | | | | 69 | | 73 |
| 30 | | | 77 | | | 35 | | | 56 |
| July 1 | | 57 | | | | 52 | | | 55 |
| 2 | | | 71 | | 58 | 40 | 52 | 65 | 57 |
| 3 | 67 | 66 | 72 | 49 | 39 | 49 | | | 57 |
| 4 | | | 58 | | | | 80 | | 69 |
| 5 | | | 39 | 33 | 32 | 46 | 68 | 62 | 47 |
| 6 | | | 77 | | | 100 | | | 89 |
| 7 | | | 78 | | | 93 | | | 86 |
| 8 | | 78 | | | | 55 | | | 67 |
| 9 | | | 68 | | | | 70 | | 69 |
| 10 | | | | 63 | | 54 | | | 59 |
| 11 | | | 80 | 49 | 45 | 54 | 64 | | 58 |
| 12 | | | | 100 | | | | | 100 |
| 13 | | | | | | | | | |
| 14 | | | | | | | | | |
| 15 | | | | | | | | | |
| 16 | | | | | | | | | |
| 17 | | | | | | | | | |
| 18 | | | | | | | | | |
| 19 | | | | | | | | | |
| 20 | | | | | | | | | |
| 21 | | | | | | | | | |
| 22 | | | | | | | | | |
| 23 | | | | | | | | | |
| 24 | | | | | | | | | |
| 25 | | | | | | | | | |
| July 26 | | | | | | | | | |

TABLE 23

PRECIPITATION (MM)
TUNDRA CAMP
1987 FIELD SEASON

| Mth/Day | 0300 | 0600 | 0900 | 1200 | 1500 | 1800 | 2100 | 0000 | Daily Total |
|---|---|---|---|---|---|---|---|---|---|
| June 28 | | | | | | M | | | M |
| 29 | | | 0.0 | | | | 0.0 | | 0.0 |
| 30 | | | T | | | 0.0 | | | 0.0 |
| July 1 | | 0.0 | | | | 0.0 | | | 0.0 |
| 2 | | | 0.0 | | 0.0 | 0.0 | 0.0 | T | 0.0 |
| 3 | 0.0 | 0.0 | T | 0.0 | 0.0 | 0.0 | | | 0.0 |
| 4 | | | 0.0 | | | | T | | 0.0 |
| 5 | | | 0.0 | 0.0 | 0.0 | 0.0 | T | T | 0.0 |
| 6 | | | 1.5 | | | 6.4 | | | 7.9 |
| 7 | | | 1.5 | | | 7.9 | | | 9.4 |
| 8 | | 0.0 | | | | T | | | 0.0 |
| 9 | | | T | | | | T | | 0.0 |
| 10 | | | | T | | 0.0 | | | 0.0 |
| 11 | | | T | 0.0 | 0.0 | 0.0 | 0.0 | | 0.0 |
| 12 | | | | 1.5 | | 0.8 | | | 2.3 |
| 13 | | | 6.4 | | | | T | | 6.4 |
| 14 | | | 15.8 | | | 15.8 | | | 31.6 |
| 15 | | | 4.8 | | | 1.5 | | | 6.3 |
| 16 | | | T | | | T | | | 0.0 |
| 17 | | | | T | | | 0.0 | | 0.0 |
| 18 | | | 3.0 | | | | 3.0 | | 6.0 |
| 19 | | | 0.0 | | | | 0.0 | | 0.0 |
| 20 | | | 0.0 | | | | T | | 0.0 |
| 21 | | | | 1.5 | | 0.0 | | | 1.5 |
| 22 | | | | | 15.8 | | | | 15.8 |
| 23 | | 28.4 | | | | | 0.0 | | 28.4 |
| 24 | | | | | | | 4.8 | | 4.8 |
| 25 | | | 0.0 | | | | 0.0 | | 0.0 |
| July 26 | | 0.0 | | | | | 0.0 | | 0.0 |

TABLE 24

WIND SPEED (Meters/Second)
TUNDRA CAMP
1987 FIELD SEASON

| Mth/Day | 0300 | 0600 | 0900 | 1200 | 1500 | 1800 | 2100 | 0000 | Daytime Mean |
|---|---|---|---|---|---|---|---|---|---|
| June 28 | | | | 1.0 | | 1.4 | | | 1.2 |
| 29 | | | 2.4 | | | | 1.4 | | 1.9 |
| 30 | | | 1.0 | | | 1.0 | | | 1.0 |
| July 1 | | 0.0 | | | | 1.0 | | | 0.5 |
| 2 | | | 0.5 | | 1.0 | 1.9 | 1.4 | 1.0 | 1.2 |
| 3 | 0.5 | 1.0 | 1.0 | 1.0 | 2.4 | 3.4 | | | 1.6 |
| 4 | | | 1.0 | | | | 1.0 | | 1.0 |
| 5 | | | 0.5 | 3.9 | 1.4 | 1.4 | 1.9 | 1.4 | 1.8 |
| 6 | | | 0.0 | | | 1.4 | | | 0.7 |
| 7 | | | 0.0 | | | 2.4 | | | 1.2 |
| 8 | | 0.5 | | | | 1.0 | | | 0.8 |
| 9 | | | >0 | | | | 0.0 | | 0.0 |
| 10 | | | | 3.9 | | 3.4 | | | 3.7 |
| 11 | | | 3.4 | 2.4 | 1.9 | 1.9 | 2.9 | | 2.5 |
| 12 | | | | 1.9 | | 1.4 | | | 1.7 |
| 13 | | | 0.0 | | | | 0.5 | | 0.3 |
| 14 | | | 0.0 | | | 0.5 | | | 0.3 |
| 15 | | | 0.5 | | | 2.4 | | | 1.5 |
| 16 | | | 1.4 | | | 1.0 | | | 1.2 |
| 17 | | | | 1.0 | | | 2.4 | | 1.7 |
| 18 | | | 0.0 | | | | 0.5 | | 0.3 |
| 19 | | | 0.0 | | | | 1.0 | | 0.5 |
| 20 | | | 1.4 | | | | 0.0 | | 0.7 |
| 21 | | | | 0.0 | | 0.5 | | | 0.3 |
| 22 | | | | | 1.0 | | | | 1.0 |
| 23 | | 0.5 | | | | | 2.4 | | 1.5 |
| 24 | | | | | | | 1.4 | | 1.4 |
| 25 | | | 2.4 | | | 2.9 | | | 2.7 |
| July 26 | | 0.0 | | | | | 0.5 | | 0.3 |

TABLE 25

WIND DIRECTION (360 Degree Azimuth)
TUNDRA CAMP
1987 FIELD SEASON

| Mth/Day | 0300 | 0600 | 0900 | 1200 | 1500 | 1800 | 2100 | 0000 | Prevailing Daytime Wind |
|---|---|---|---|---|---|---|---|---|---|
| June 28 | | | | 340 | | 315 | | | |
| 29 | | | 360 | | | | 360 | | 360 |
| 30 | | | 360 | | | 360 | | | 360 |
| July 1 | | None | | | | 360 | | | 360 |
| 2 | | | 360 | | 360 | 360 | 360 | 360 | 360 |
| 3 | 70 | 360 | 360 | 360 | 360 | 360 | | | 360 |
| 4 | | | 360 | | | | 360 | | 360 |
| 5 | | | 360 | 360 | 360 | 180 | 180 | 360 | 360 |
| 6 | | | 360 | | | 180 | | | |
| 7 | | | None | | | 360 | | | 360 |
| 8 | | 360 | | | | 135 | | | |
| 9 | | | 360 | | | | None | | 360 |
| 10 | | | | 360 | | 360 | | | 360 |
| 11 | | | 360 | 360 | 360 | 180 | 360 | | 360 |
| 12 | | | | 180 | | 360 | | | |
| 13 | | | None | | | | 360 | | 360 |
| 14 | | | None | | | 180 | | | 180 |
| 15 | | | 360 | | | 360 | | | 360 |
| 16 | | | 180 | | | 180 | | | 180 |
| 17 | | | | 360 | | | 360 | | 360 |
| 18 | | | None | | | | 270 | | 270 |
| 19 | | | None | | | | 360 | | 360 |
| 20 | | | 360 | | | | None | | 360 |
| 21 | | | | None | | 180 | | | 180 |
| 22 | | | | | 180 | | | | 180 |
| 23 | | 180 | | | | | 180 | | 180 |
| 24 | | | | | | | | 180 | 180 |
| 25 | | | 360 | | | 360 | | | 360 |
| July 26 | | None | | | | | 360 | | 360 |

## TABLE 26

CLOUD COVER (Tenths)
TUNDRA CAMP
1987 FIELD SEASON

| Mth/Day | 0300 | 0600 | 0900 | 1200 | 1500 | 1800 | 2100 | 0000 | Daytime Mean |
|---|---|---|---|---|---|---|---|---|---|
| June 28 | | | | 10 | | 10 | | | 10 |
| 29 | | | 10 | | | | 9 | | 10 |
| 30 | | | 10 | | | 6 | | | 8 |
| July 1 | | 5 | | | | 10 | | | 8 |
| 2 | | | 8 | | | 5 | 9 | 10 | 7 |
| 3 | 9 | 8 | 8 | 8 | 9 | 8 | | | 8 |
| 4 | | | 9 | | | | 6 | | 8 |
| 5 | | | 1 | 2 | 2 | 8 | 10 | 10 | 3 |
| 6 | | | 10 | | | 10 | | | 10 |
| 7 | | | 10 | | | 10 | | | 10 |
| 8 | | | 7 | | | 9 | | | 8 |
| 9 | | | 9 | | | | 8 | | 9 |
| 10 | | | | 9 | | 10 | | | 10 |
| 11 | | | 8 | 9 | 10 | 9 | 9 | | 9 |
| 12 | | | | 10 | | 10 | | | 10 |
| 13 | | | 9 | | | | 1 | | 9 |
| 14 | | | 10 | | | 10 | | | 10 |
| 15 | | | 10 | | | 10 | | | 10 |
| 16 | | | 8 | | | 10 | | | 9 |
| 17 | | | | 10 | | | 9 | | 10 |
| 18 | | | 10 | | | | 7 | | 10 |
| 19 | | | 5 | | | | 6 | | 5 |
| 20 | | | 8 | | | | 10 | | 8 |
| 21 | | | | 8 | | 7 | | | 8 |
| 22 | | | | | 10 | | | | 10 |
| 23 | | 9 | | | | | 7 | | 9 |
| 24 | | | | | | | | 10 | M |
| 25 | | | 4 | | | 5 | | | 5 |
| July 26 | | 0 | | | | | 0 | | 0 |

## TABLE 27

ESTIMATED CEILING OF CLOUD COVER (Meters)
TUNDRA CAMP
1987 FIELD SEASON

| Mth/Day | 0300 | 0600 | 0900 | 1200 | 1500 | 1800 | 2100 | 0000 | Average Ceiling |
|---|---|---|---|---|---|---|---|---|---|
| June 28 | | | | 600 | | 600 | | | 600 |
| 29 | | | 750 | | | | 900 | | 825 |
| 30 | | | 750 | | | 900 | | | 825 |
| July 1 | | | 1200 | | | 1200 | | | 1200 |
| 2 | | | 1200 | | 750 | 900 | 900 | 900 | 930 |
| 3 | 1050 | 1050 | 1200 | 1200 | 900 | 1200 | | | 1100 |
| 4 | | | 1050 | | | | 900 | | 975 |
| 5 | | | 1200 | 1500 | 600 | 600 | 600 | 750 | 875 |
| 6 | | | 300 | | | 0 | | | 150 |
| 7 | | | 125 | | | 300 | | | 213 |
| 8 | | 1200 | | | | 1200 | | | 1200 |
| 9 | | | 1500 | | | | 1200 | | 1350 |
| 10 | | | | 600 | | 600 | | | 600 |
| 11 | | | 600 | 750 | 600 | 600 | 750 | | 660 |
| 12 | | | | 60 | | 175 | | | 118 |
| 13 | | | 200 | | | | 1500 | | 850 |
| 14 | | | 175 | | | 60 | | | 118 |
| 15 | | | 150 | | | 300 | | | 225 |
| 16 | | | 600 | | | 750 | | | 675 |
| 17 | | | | | | | 600 | | 600 |
| 18 | | | 90 | | | | 600 | | 345 |
| 19 | | | 1500 | | | | 1200 | | 1350 |
| 20 | | | 6000 | | | | 300 | | 3150 |
| 21 | | | | 300 | | 1500 | | | 900 |
| 22 | | | | | 750 | | | | 750 |
| 23 | | 300 | | | | | 1050 | | 675 |
| 24 | | | | | | | 1200 | | 1200 |
| 25 | | | 1200 | | | 900 | | | 1050 |
| July 26 | | | CAVU | | | | CAVU | | |

TABLE 28

CLOUD TYPE
TUNDRA CAMP
1987 FIELD SEASON

| Mth/Day | 0600 | 0900 | 1200 | 1500 | 1800 | 2100 |
|---|---|---|---|---|---|---|
| June 28 | | | St | | St | |
| 29 | | St | | | | St8/Ci1 |
| 30 | | St | | | St4/Ci2 | |
| July 1 | St2/Ci3 | | | | St | |
| 2 | | St5/Ci2/Cu1 | | St | Sc4/Cs1 | St |
| 3 | St | St | Sc | St | St | |
| 4 | | St | | | | Sc |
| 5 | | St/Sc | Sc | Sc2/Ci | Sc | St |
| 6 | | St | | | Ns | |
| 7 | | Ns | | | Ns | |
| 8 | Cu1/St3/Ci3 | | | | Cu2/St7 | |
| 9 | | St | | | | St |
| 10 | | | St | | St | |
| 11 | | St | Sc | St7/Cu3 | St7/Cu2 | St8/Cu1 |
| 12 | | | Ns | | St | |
| 13 | | St | | | | Cu |
| 14 | | Ns | | | Ns | |
| 15 | | St | | | St | |
| 16 | | Sc6/Cu2 | | | St | |
| 17 | | | St | | | St |
| 18 | | Ns | | | | Sc |
| 19 | | Cu | | | | Cu3/Ci3 |
| 20 | | As | | | | St9/Cu1 |
| 21 | | | Scu | | Ci2/Cu5 | |
| 22 | | | | Ns | | |
| 23 | Sc | | | | | Sc |
| 24 | | | | | | St |
| 25 | | Ci1/Cu3 | | | Cu2/Ci3 | |
| July 26 | | | | | | |

TABLE 29

CLOUD MOVEMENT (360 Degree Azimuth)
TUNDRA CAMP
1987 FIELD SEASON

| Mth/Day | 0300 | 0600 | 0900 | 1200 | 1500 | 1800 | 2100 | 0000 | Daytime Mode |
|---|---|---|---|---|---|---|---|---|---|
| June 28 | | | | None | | None | | | |
| 29 | | | None | | | | None | | |
| 30 | | | None | | | 180 | | | |
| July 1 | | 135 | | | | None | | | |
| 2 | | | 45 | | None | None | 360 | None | |
| 3 | None | None | None | None | None | None | | | |
| 4 | | | None | | | | None | | |
| 5 | | | None | None | None | None | 135 | 135 | |
| 6 | | | 360 | | | 180 | | | |
| 7 | | | 180 | | | None | | | |
| 8 | | 135 | | | | None | | | |
| 9 | | | None | | | | None | | |
| 10 | | | | 360 | | None | | | |
| 11 | | | None | 360 | 360 | 360 | 360 | | 360 |
| 12 | | | | 180 | | None | | | |
| 13 | | | None | | | | 113 | | |
| 14 | | | None | | | None | | | |
| 15 | | | None | | | None | | | |
| 16 | | | 180 | | | 180 | | | 180 |
| 17 | | | | None | | | 180 | | |
| 18 | | | None | | | | 270 | | |
| 19 | | | None | | | | None | | |
| 20 | | | None | | | | None | | |
| 21 | | | | 180 | | 180 | | | 180 |
| 22 | | | | | 180 | | | | 180 |
| 23 | | 180 | | | | | 360 | | |
| 24 | | | | | | | | None | |
| 25 | | | None | | | None | | | |
| July 26 | | None | | | | | None | | |

TABLE 30

VISIBILITY TO SOUTH (KM)
TUNDRA CAMP
1987 FIELD SEASON

| Mth/Day | 0300 | 0600 | 0900 | 1200 | 1500 | 1800 | 2100 | 0000 | Mean Visibility Daily |
|---|---|---|---|---|---|---|---|---|---|
| June 28 | | | | >50 | | >50 | | | >50 |
| 29 | | | >50 | | | | >50 | | >50 |
| 30 | | | 50.0 | | | >50 | | | 50.0 |
| July 1 | | >50 | | | | 50.0 | | | 50.0 |
| 2 | | | 50.0 | | 50.0 | >50 | >50 | >50 | 50.0 |
| 3 | >50 | >50 | >50 | >50 | >50 | 50.0 | | | 50.0 |
| 4 | | | 50.0 | | | | >50 | | 50.0 |
| 5 | | | >50 | >50 | >50 | 50.0 | 50.0 | 30.0 | 46.7 |
| 6 | | | >8 | | | 0.1 | | | 4.1 |
| 7 | | | 0.8 | | | >50 | | | 25.4 |
| 8 | | | >50 | | | >50 | | | >50 |
| 9 | | | >50 | | | | 50.0 | | 50.0 |
| 10 | | | | 50.0 | | 40.0 | | | 45.0 |
| 11 | | | >50 | 50.0 | 40.0 | 40.0 | >50 | | 46.0 |
| 12 | | | | 0.8 | | 40.0 | | | 20.4 |
| 13 | | | 15.0 | | | | >50 | | 32.5 |
| 14 | | | 6.0 | | | 0.4 | | | 3.2 |
| 15 | | | 2.5 | | | 50.0 | | | 26.3 |
| 16 | | | >50 | | | 50.0 | | | 50.0 |
| 17 | | | | 50.0 | | | >50 | | 50.0 |
| 18 | | | 15.0 | | | | >50 | | 32.5 |
| 19 | | | >50 | | | | 50.0 | | 50.0 |
| 20 | | | 50.0 | | | | 50.0 | | 50.0 |
| 21 | | | | >50 | | >50 | | | >50 |
| 22 | | | | | 15.0 | | | | 15.0 |
| 23 | | >25 | | | | | 40.0 | | 32.5 |
| 24 | | | | | | | 25.0 | | 25.0 |
| 25 | | | 40.0 | | | >50 | | | 45.0 |
| July 26 | | >50 | | | | | >50 | | >50 |

TABLE 31

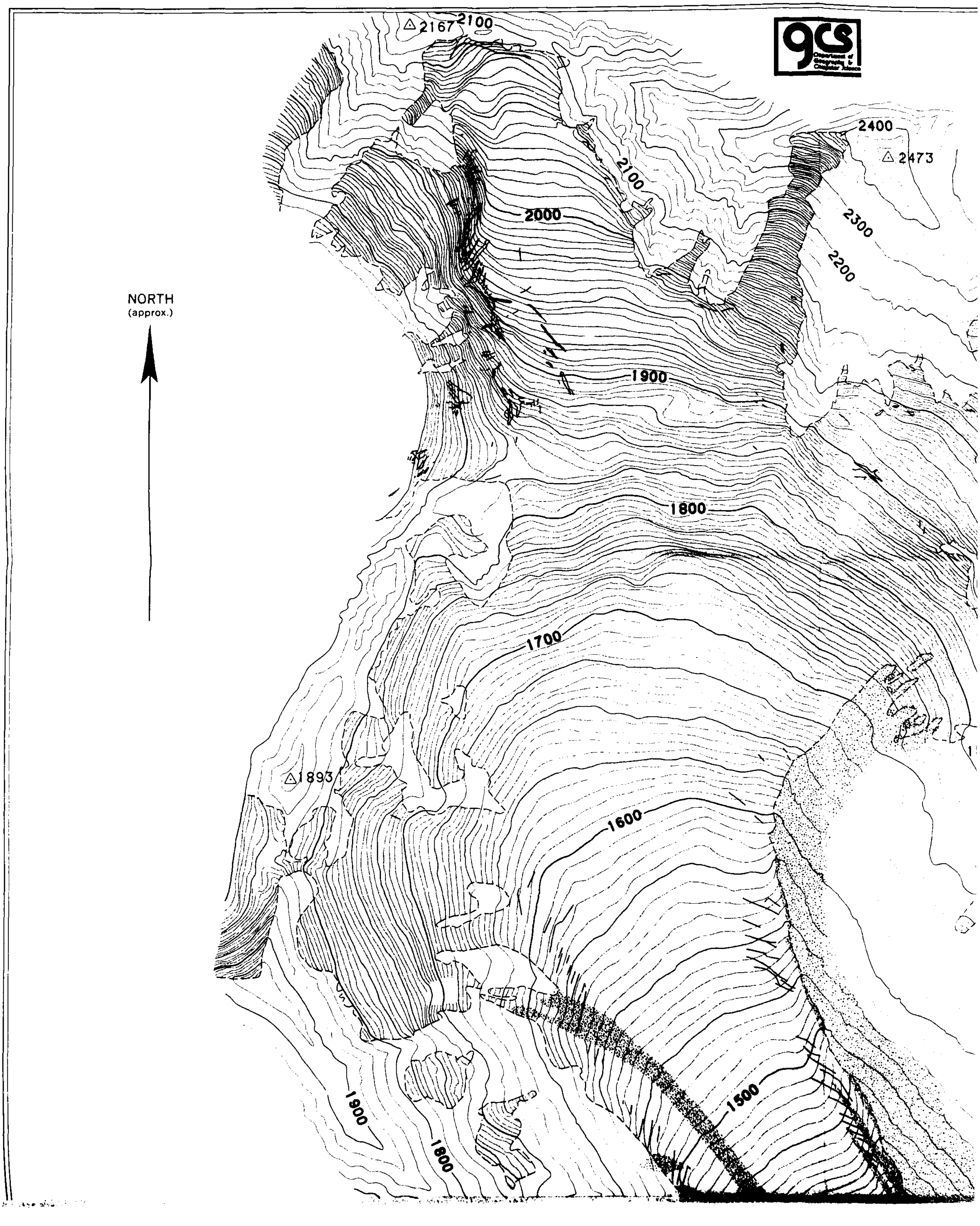
VISIBILITY TO NORTH (KM)
TUNDRA CAMP
1987 FIELD SEASON

| Mth/Day | 0300 | 0600 | 0900 | 1200 | 1500 | 1800 | 2100 | 0000 | Mean Visibility Daily |
|---|---|---|---|---|---|---|---|---|---|
| June 28 | | | | 5.0 | | 4.0 | | | 4.5 |
| 29 | | | 5.0 | | | | 5.0 | | 5.0 |
| 30 | | | 3.0 | | | >5 | | | 4.0 |
| July 1 | | >5 | | | | 3.0 | | | 4.0 |
| 2 | | | 5.0 | | 3.0 | >3 | 3.0 | 3.0 | 3.4 |
| 3 | 3.0 | 5.0 | 5.0 | >5 | >5 | >5 | | | 4.7 |
| 4 | | | >5 | | | | 5.0 | | 5.0 |
| 5 | | | >5 | >5 | >5 | 5.0 | 5.0 | 5.0 | 5.0 |
| 6 | | | 3.0 | | | 0.1 | | | 1.6 |
| 7 | | | 1.2 | | | 2.5 | | | 1.9 |
| 8 | | >3 | | | | 5.0 | | | 4.0 |
| 9 | | | 5.0 | | | | >5 | | 5.0 |
| 10 | | | | 2.5 | | 3.0 | | | 3.3 |
| 11 | | | 3.0 | 2.5 | 3.0 | 3.0 | 3.0 | | 2.9 |
| 12 | | | | 1.5 | | 1.5 | | | 1.5 |
| 13 | | | 2.5 | | | | >5 | | 3.8 |
| 14 | | | 1.5 | | | 0.2 | | | 0.9 |
| 15 | | | 1.5 | | | 3.0 | | | 2.3 |
| 16 | | | 3.0 | | | 3.0 | | | 3.0 |
| 17 | | | | 3.0 | | | 3.0 | | 3.0 |
| 18 | | | 1.5 | | | | 2.5 | | 2.0 |
| 19 | | | 2.5 | | | | >5 | | 3.8 |
| 20 | | | >5 | | | | 4.0 | | 4.5 |
| 21 | | | | 3.0 | | 4.0 | | | 3.5 |
| 22 | | | | | 4.0 | | | | 4.0 |
| 23 | | 5.0 | | | | | 2.5 | | 3.8 |
| 24 | | | | | | | | 2.5 | 2.5 |
| 25 | | | >5 | | | 4.0 | | | 4.5 |
| July 26 | | >5 | | | | | >5 | | >5 |

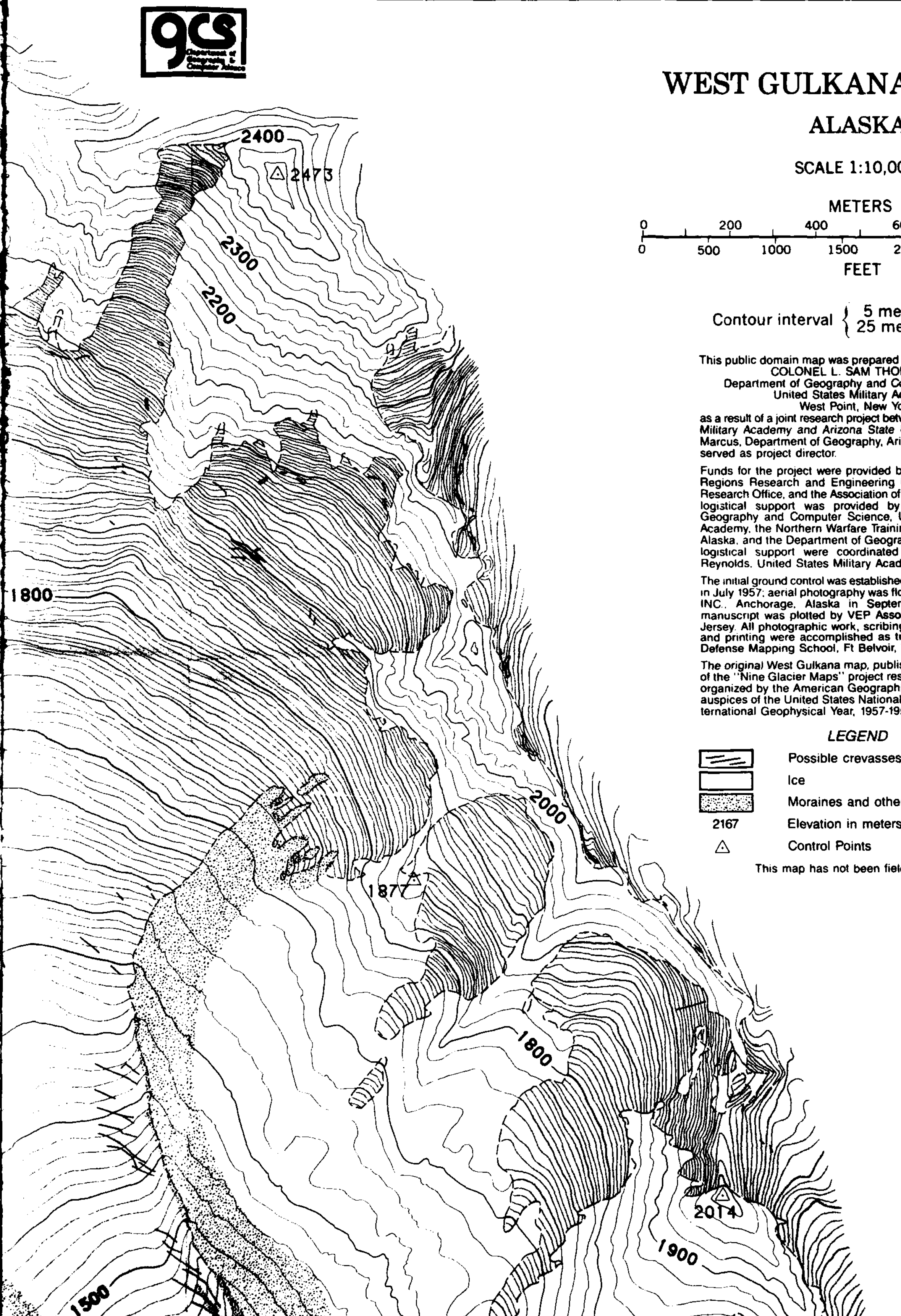
TABLE 32

MAXIMUM & MINIMUM TEMPERATURES (Degrees C)
TERMINUS STATION
1986 & 1987 FIELD SEASONS

| 1986 Month/Day | Maximum | Minimum | 1987 Month/Day | Maximum | Minimum |
|---|---|---|---|---|---|
| June 21 | | | June 28 | 7.2 | |
| 22 | 11.1 | | 29 | 12.2 | 3.3 |
| 23 | 7.2 | 1.7 | 30 | 10.0 | 4.4 |
| 24 | 7.8 | 2.8 | July 1 | 7.8 | 4.4 |
| 25 | 10.6 | 1.1 | 2 | 11.1 | 5.0 |
| 26 | 8.9 | 2.2 | 3 | 13.9 | 4.4 |
| 27 | 15.0 | 5.6 | 4 | 13.3 | M |
| 28 | 15.6 | 5.6 | 5 | M | M |
| 29 | 17.2 | 7.8 | 6 | 14.4 | M |
| 30 | 20.0 | 7.2 | 7 | 6.7 | 3.9 |
| July 1 | 20.6 | 10.0 | 8 | 3.9 | 1.7 |
| 2 | 20.0 | 12.2 | 9 | 7.8 | 3.3 |
| 3 | 18.3 | 11.1 | 10 | 8.3 | 3.3 |
| 4 | 16.7 | 9.4 | 11 | 10.6 | 3.9 |
| 5 | 19.5 | 8.9 | 12 | 10.0 | 4.4 |
| 6 | 17.8 | 8.9 | 13 | 10.0 | 3.3 |
| 7 | 19.5 | 8.3 | 14 | 5.6 | 2.8 |
| 8 | 10.6 | 7.8 | 15 | 6.1 | 2.8 |
| 9 | 14.6 | 8.3 | 16 | 10.6 | 3.9 |
| 10 | 16.7 | 8.3 | 17 | 6.7 | 3.3 |
| 11 | 13.3 | 8.9 | 18 | 7.2 | 4.4 |
| 12 | 21.1 | 8.9 | 19 | 10.0 | 4.4 |
| 13 | 10.6 | 6.7 | 20 | 18.9 | 6.1 |
| 14 | 17.5 | 6.7 | 21 | 11.1 | 4.4 |
| 15 | 13.3 | 10.0 | 22 | 10.0 | 3.9 |
| 16 | 18.9 | 8.9 | 23 | 12.2 | 2.8 |
| 17 | 25.0 | 12.2 | 24 | 12.8 | 4.4 |
| 18 | 17.2 | 11.1 | 25 | 12.2 | 3.9 |
| July 19 | 11.1 | 8.3 | July 26 | 12.8 | 6.1 |
| Average | 15.6 | 7.7 | | 10.1 | 3.9 |



NORTH
(approx.)
△2167
2100
2400
△2473
2100
2000
2300
2200
1900
1800
1700
△1893
1600
1500
1900
1800




# WEST GULKANA GLACIER

## ALASKA

SCALE 1:10,000

METERS
0 200 400 600 800 1000
0 500 1000 1500 2000 2500 3000
FEET

Contour interval { 5 meters on glacier / 25 meters elsewhere

This public domain map was prepared under the direction of COLONEL L. SAM THOMPSON Department of Geography and Computer Science United States Military Academy West Point, New York as a result of a joint research project between the United States Military Academy and Arizona State University. Dr. Melvin Marcus, Department of Geography, Arizona State University, served as project director.

Funds for the project were provided by the U.S. Army Cold Regions Research and Engineering Laboratory, the Army Research Office, and the Association of Graduates. Invaluable logistical support was provided by the Department of Geography and Computer Science, United States Military Academy, the Northern Warfare Training Center, Ft Greeley, Alaska, and the Department of Geography, ASU. Funds and logistical support were coordinated by Colonel William Reynolds, United States Military Academy.

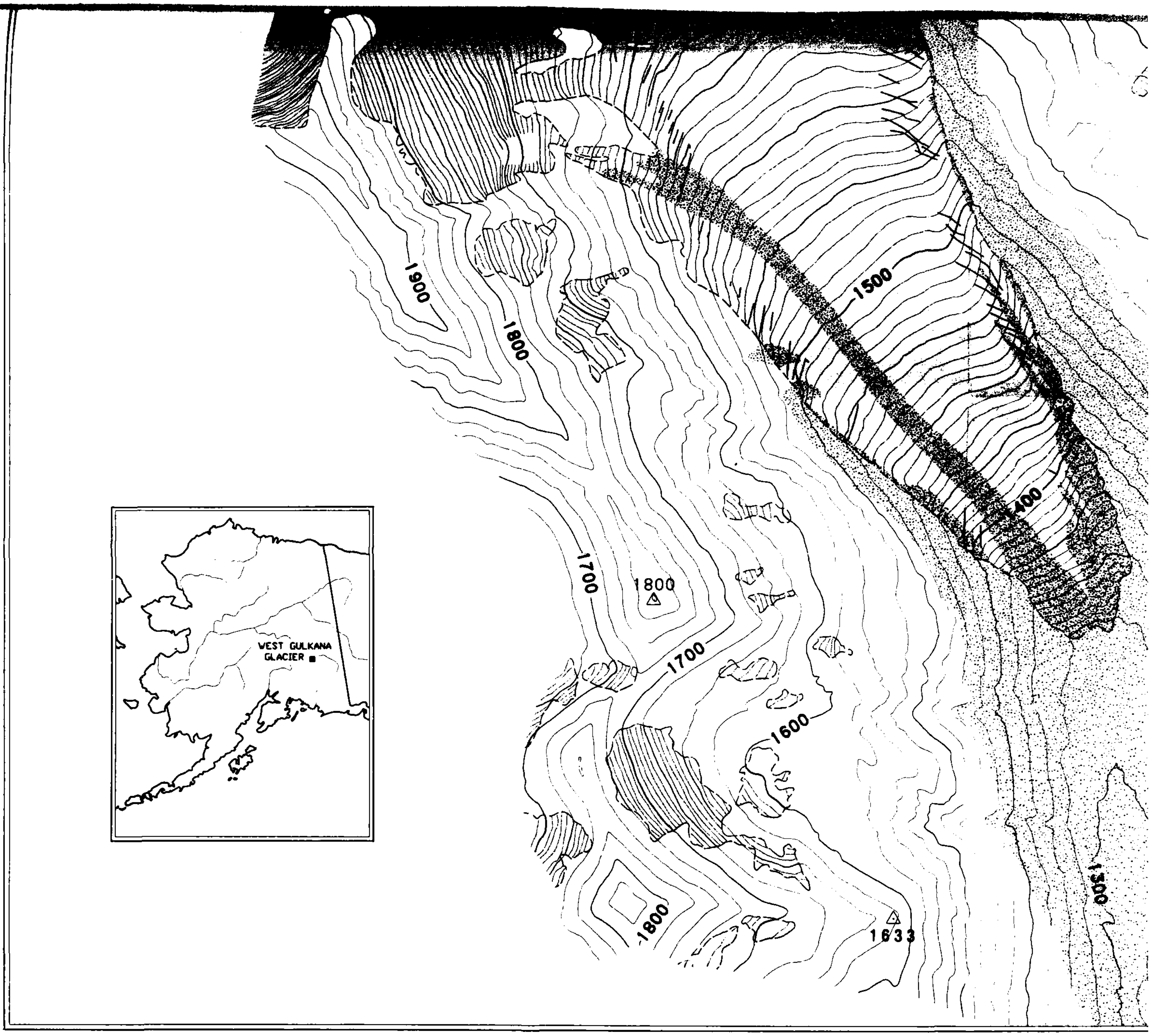
The initial ground control was established by Dr. James B. Case in July 1957; aerial photography was flown by Air Photo Tech, INC., Anchorage, Alaska in September 1986; and the manuscript was plotted by VEP Associates, Caldwell, New Jersey. All photographic work, scribing, layout, platemaking and printing were accomplished as training projects at the Defense Mapping School, Ft Belvoir, Virginia.

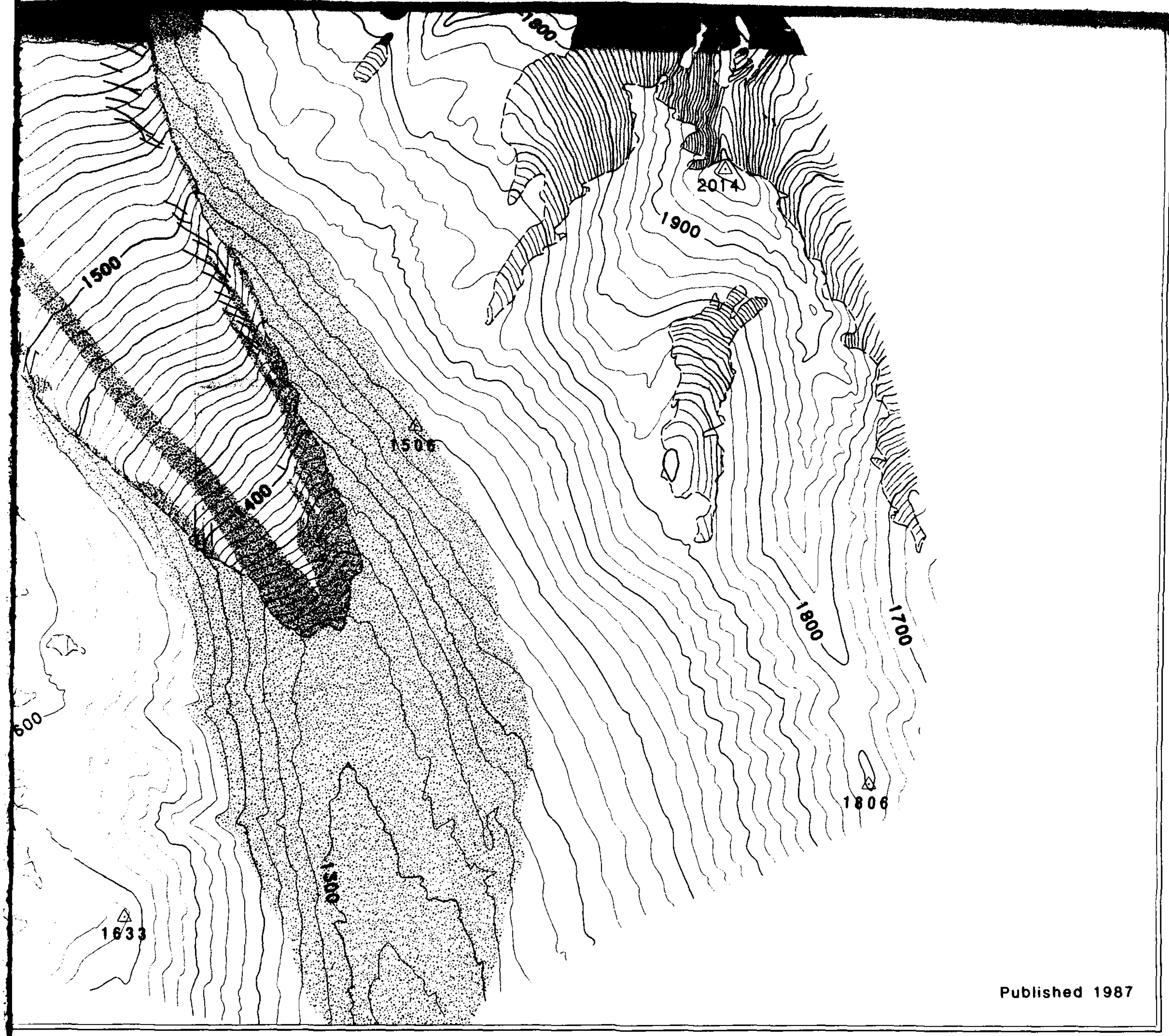
The original West Gulkana map, published in 1960, was part of the "Nine Glacier Maps" project resulting from a program organized by the American Geographical Society under the auspices of the United States National Committee for the International Geophysical Year, 1957-1958.

*LEGEND*

| | |
|---|---|
| | Possible crevasses and bergschrunds |
| | Ice |
| | Moraines and other glacial deposits |
| 2167 | Elevation in meters |
| △ | Control Points |

This map has not been field checked.


1900
1800
1500
1400
1700
1800
1700
1600
1800
1633
1300
WEST GULKANA
GLACIER




Published 1987